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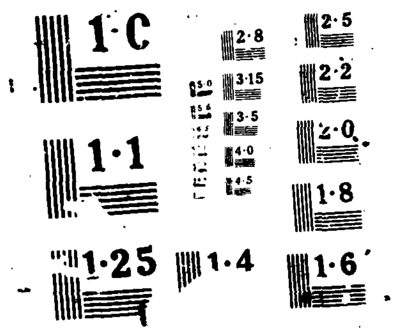
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A GAMS-BASED MODEL OF THE U.S. ARMY WARTIME AMMUNITION DISTRIBUTION SYSTEM FOR THE CORPS LEVEL

by

Mark J. Cain

March 1988

Thesis Advisor: R. Kevin Wood

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The U.S. Army Wartime Ammunition Distribution System (WADS) will experience an unprecedented demand for ammunition under the operational concept of Airland Battle. To meet demand, proper storage facility location and an efficient flow through the distribution network will be required.

Using information from Army Field Manuals, maps and simulation data for demand, both a mixed integer program (MIP) and a sequential, optimization-based heuristic are developed to model the WADS. The Generalized Algebraic Modelling System is used to implement both models. The sequential heuristic locates ammunition facilities with a binary integer program and then directs ammunition through those facilities utilizing a network flow model with side constraints. The MIP integrates location and flow decisions in the same model. For a general scenario, the sequential heuristic locates a 21 node, 30 arc network with ammunition flows over 30 time periods in 22 CPU seconds on an IBM 3033AP. For the same scenario the MIP obtains a solution for only a 3 time period problem in 87 CPU seconds.

Results indicate shortcomings in the WADS as it currently exists. The models and analysis show that current doctrine is infeasible unless there is an increase in lift assets at the Corps level storage facilities and a reduction in inventory goals at the Ammunition Supply Points.

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A GAMS-Based Model of the U.S. Army Wartime Ammunition
Distribution System for the Corps Level

by

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Captain, United States Army
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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The U.S. Army Wartime Ammunition Distribution System (WADS) will experience an unprecedented demand for ammunition under the operational concept of Airland Battle. To meet demand, proper storage facility location and an efficient flow through the distribution network will be required.

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Results indicate shortcomings in the WADS as it currently exists. The models and analysis show that current doctrine is infeasible unless there is an increase in lift assets at the Corps level storage facilities and a reduction in inventory goals at the Ammunition Supply Points.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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God Bless you all!

I. INTRODUCTION

The U.S. Army Wartime Ammunition Distribution System (WADS) is presently based on heuristics or "rules of thumb" developed from the experience gained during World War II, Korea and Vietnam. The concept of Airland Battle, developed since Vietnam, has generated concern within the Army's ammunition analytical community because, using this concept, a greater demand for ammunition will be placed on the WADS.

This thesis develops an integrated model which concurrently locates ammunition facilities and determines proper ammunition flow using a mixed integer program. However, because of limited solution capabilities, a sequential, optimization-based heuristic is developed which decomposes the problem. The sequential heuristic is composed of two optimizing submodels, an ammunition storage facility location submodel and an ammunition network flow submodel. Both models are developed to test current doctrine and provide a tool for analysis of future systems.

A. AIRLAND BATTLE

The concept of Airland Battle is simply a means to defeat a large armored force which attacks by echelon, through a narrow breach sector in an opponent's front; Soviet bloc forces are the attackers and the Western forces are the defenders.

The idea of Airland Battle is to defeat the armored force's first two echelons at the proposed breach point and then use a deep attack to disrupt any further flow of the third and successive echelons forward. Deep attack might be USAF fighter aircraft or bombers, conventional cruise missiles, special operations forces, tactical nuclear weapons, etc. This concept differs from prior ideas since our forward units are now required to defeat two echelons rather than the one echelon of past conflicts. Defeating two echelons will require more ammunition per unit engaged with the enemy. Ammunition consumption will increase (Figure 1 on page 2).

The concept of Airland Battle is dynamic since it requires our widely spread forces to move to a breach point and concentrate assets to defeat the first two enemy echelons. Firepower far superior to that used in past conflicts will be required to defeat the enemy at the breach point. To achieve superior firepower, a greater demand for ammunition will be required than in past wars. Ammunition must arrive forward in the type and

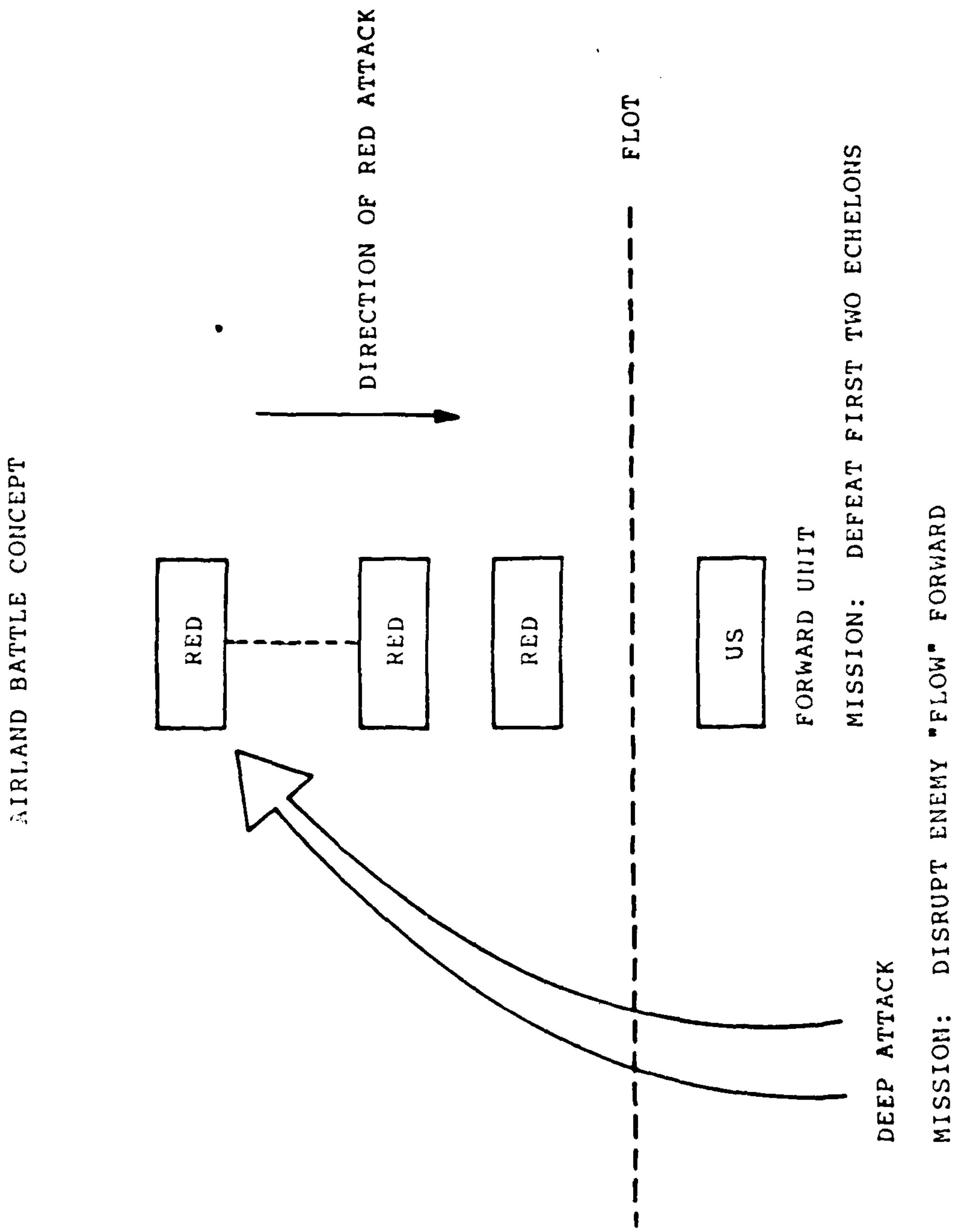

Figure 1. Airland Battle

quantity required; a stockout situation during an enemy attack would most likely be fatal.

The ammunition community claims that even in past conflicts,

> "Ammunition availability constrains combat power before shortages of combat vehicles, crews, maintenance, repair parts, and POL [Ref. 1]."

So, concisely, the problem is to move ammunition forward to meet demand in the most expeditious manner possible subject to available assets and subject to constraints on vulnerability which result from large inventory build-ups.

B. PROBLEM SCOPE AND PURPOSE

This thesis examines the problems associated with locating ammunition storage facilities and determining an efficient flow of ammunition between storage facilities within a generic Corps in a Theater of Operations (TO). Network structure above the Corps level, i.e. Port, Theater Storage Area, and associated transportation links, will not be considered due to program and computer size restrictions. In addition, Port and TSA facilities are generally fixed [Ref. 2 p.68] so they are not appropriate for the models developed. A scenario is set in Korea for which realistic data can be extracted from available maps [Ref. 3]. Consumption data is provided by the U.S. Army Ordnance, Missile, and Munitions Center (USAOMMCS) [Ref. 4]. The general network structure is extracted from applicable Army Field Manuals [Ref. 5 pp.2-78]. Since specific consumption rates and force structures tied to a theater are classified, our scenario is deliberately general and represents figures which are realistic but but not precise.

The purpose of this research is to model the WADS using current doctrine to indicate where changes should be made. As a result of model development, a tool for analysis of future systems is presented which, with minor changes to the source code, is complete for use (assuming availability of the GAMS software).

C. THE MODEL AND SOLUTION PROCEDURE

Using the aforementioned scenario, an integrated approach to the overall optimization problem is described and preliminary computational results given. However, results with the integrated model are extremely limited because it is too large for the available solver. Consequently, an alternate modelling approach is described and analyzed at length.

A sequential heuristic which uses a separation technique solves the scenario of interest. First, a binary integer program locates the ammunition facilities within a Corps area. Then, facility location data is passed to a network flow model to determine optimal movement of ammunition forward from the Corps rear to the combat units in the brigade area. The Generalized Algebraic Modelling System (GAMS) implements the heuristic using a sequential solving procedure.

A natural approach to this analysis might be through stochastic inventory theory. However, this approach cannot be used since distributional demand data is not available. To date, ammunition consumption in combat has only been roughly correlated to activity, i.e. first day of defense, first day of offense, etc. The Concepts Analysis Agency and the Combined Arms Center are presently working on distribution issues [Ref. 6]. Unfortunately, preliminary results are not available. Therefore, wide use of combat simulations provides synthetic data which is currently used for most analysis and will be used in this thesis.

D. OUTLINE

This thesis presents an integrated and a sequential approach to locate ammunition facilities and determine proper flow. Chapter II outlines the WADS as it currently exists and describes some concepts under development to improve performance of the system. Chapter III develops the integrated model and the sequential heuristic. The facility location and network flow portions of each model are discussed. Both models have remarks concerning GAMS implementation and highlights of techniques used to construct solvable formulations given sufficient CPU time and computer memory. Chapter IV discusses computational experience of the integrated approach and the sequential heuristic. Advantages and disadvantages of the two procedures are given. Model behavior is outlined which forms the basis for conclusions drawn concerning current doctrine. Chapter V contains conclusions and recommendations for further research. Appendices include the GAMS code for the integrated model and the sequential heuristic.

II. THE ARMY WARTIME AMMUNITION DISTRIBUTION SYSTEM

This chapter outlines the procedures and structure of the Wartime Ammunition Distribution System (WADS). The current system and future developments are discussed. Procedures and structure presented provide the basis for model development discussed in Chapter III.

A. CURRENT AND FUTURE STRUCTURE

The WADS [Ref. 5 : pp.2-78] is modeled as an acyclic network directed from a port, which acts as a source, through a series of transshipment nodes (Theater Storage Areas, Corps Storage Areas and Ammunition Supply Points) to the Ammunition Transfer Points (ATPs) which act as sinks. Transportation links between the nodes are the arcs of the network.

Ammunition arrives from the continental United States at a port, within the TO, where it is offloaded from ships or aircraft. From the port, ammunition is moved to the Theater Storage Area (TSA) or shipped directly to the Corps Storage Areas (CSAs) and Ammunition Storage Points (ASPs). The TSAs distribute ammunition to the CSAs and ASPs. The CSAs, in turn, pass ammunition to the ASPs and ATPs. ASPs supply ammunition only to the ATPs. Supply is based on a continuous refill and is directed from the rear to forward areas. Lateral and forward-to-rear movement of ammunition is not allowed. Many different distribution networks are possible, based on tactical configurations, but a typical network in accordance with Army doctrine [Ref. 5 : pp.2-63] is shown in Figure 2 on page 6.

In general, each TSA can be expected to support two or more CSAs. Each forward division will be supported by at least one CSA. This means each CSA can support two or more ASPs. Each ASP, in turn, could support one or more ATPs. For modelling purposes in this thesis, each ASP will support two ATPs and each CSA will support two ASPs and four ATPs as indicated in Figure 2. This is the typical arrangement.

Under current doctrine, stockage of ammunition occurs at the TSA, the CSA, and the ASP on a major scale, i.e. multiple days of supply. Stockage at the ATPs is only short term, something on the order of hours versus days. Although some inconsistency exists [Ref. 7 : pp.3-38], the following table indicates stockage "rules of thumb" and approximate physical size [Ref. 2]:

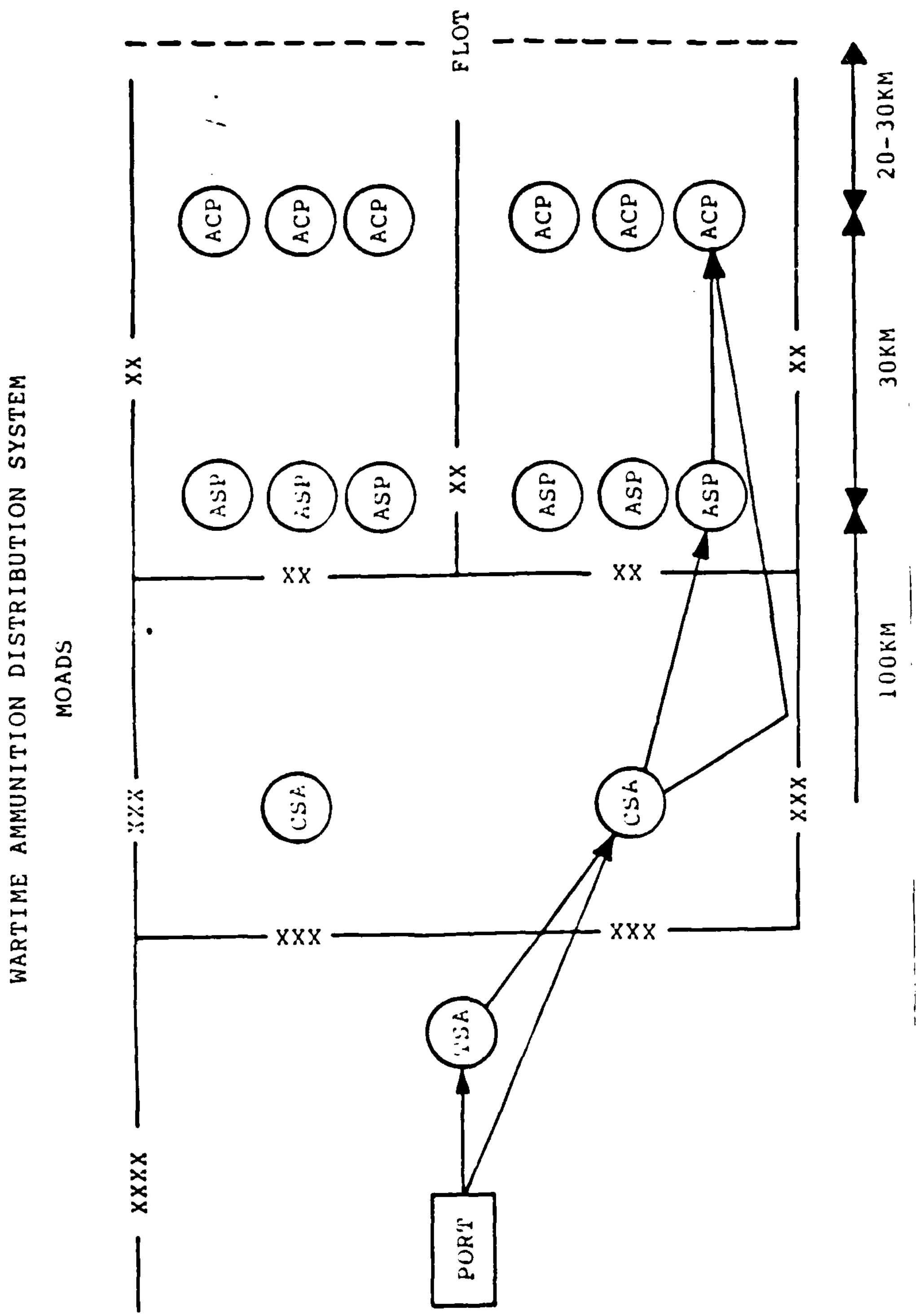

Figure 2. Current and Future Wartime Ammunition Distribution System

Table 1. SUPPLY AND SIZE DATA

FACILITY	SUPPLY	SIZE (km^2)
TSA	30 days	20+
CSA	5-7 days	16
ASP	3-5 days	9
ATP	3-4 hrs.	$<<1$

The Army uses a nebulous concept, "days of supply", to establish stockage levels. A day of supply varies with demand and is defined to be the total amount of ammunition issued by any given ATP, and subsequently consumed, during one day of combat. For instance, an ASP which supports 2 ATPs must have, according to the previous table, 3-5 days of supply on-hand for each ATP. A day of supply may vary from ATP to ATP. ATPs within a division may have varying demand rates and hence a day of supply would be different for each. This means the 2 ASPs which support a division will probably have different stockage levels since the days of supply will most likely not be the same for each ATP. Since demand is random, the "rule of thumb" for stockage can fluctuate. In actual practice, a node could have the required days of supply on-hand for a low demand period and subsequently violate the stockage rules in a matter of hours should a period with high demand occur. A day of supply may not be a very satisfactory concept but it is the one used in the Army.

By doctrine, each arc has a percentage attribute which indicates what fraction of the head node's stockage comes from the tail node. These percentages seem to be based on wartime experience and "best guesses." No analytical computations appear to exist that support the specified percentages [Ref. 6]. The term "bypass" is used to indicate an arc which goes around and not through a transshipment node. Typically, ammunition flowing on bypass arcs is high demand, high tonnage items. Low demand, low tonnage items usually flow through each transshipment node from the Port to the ATP. For an ATP, 80% of ammunition comes directly from the CSA and 20% from the ASP. At the ASP, 20% comes from the Port, 30% from the TSA, and 50% arrives directly from the CSA. The CSA receives 50% of its ammunition from the Port and 50% from the TSA. All of the TSA's ammunition comes from the Port.

ATPs are located 20-30 kilometers (km) from the forward line of troops (FLOT). ASPs are a maximum of 30 km to the rear of the ATPs they support and CSAs are 100 km to the rear of the ASPs. This yields a maximum distance of 130 km from the CSA to the ATPs it supports and 160 km from the CSA to the FLOT [Ref. 5 : pp.2-60 - 2-78].

Arcs from node to node are capacitated. The bulk of ammunition moved in the TO is by 5 ton tractors and 22.5 ton trailers and the number of tractor trailers available is finite. Specific upper and lower bounds for each arc in terms of the ability to move short tons of ammunition by tractor trailer are not assigned. The transportation community desires maximum flexibility in operations and prefers not to dedicate tractor trailers to individual arcs. By declining to dedicate assets to specific arcs, tractor trailers can be moved where needed the most. In theory, this provides the best support [Ref. 8].

A rough transportation plan to support the WADS might be calculated as follows. For each time period, find the required flows to meet inventory goals and demand over every arc in the network. The determination of proper flow must be constrained by available transportation assets whose capability to move ammunition forward will be degraded by maintenance requirements and other transportation missions, and aided by the number of round trips possible per day. The number of tractor trailers required for each time period is then found by summing all ammunition flows and dividing by average haul weight for each trailer. This roughly gives the total number of tractor trailers required for each time period.

It is estimated that 75-80% of all cargo moved within the TO will be ammunition. This means that the majority of all transportation assets will be moving ammunition forward. Flow forward along the PORT-TSA-CSA-ASP paths depends heavily on the particular characterisitics of the TO, specifically road, river and rail networks, and the level of host nation support, if any. Therefore, estimating ability to move ammunition forward is difficult. On the other hand, movement on the the CSA-ASP-ATP (Corps level) paths is better defined. The Corps level set of arcs is supported almost exclusively by tactical wheeled vehicles; primarily the 5 ton tractor and the 22.5 ton trailer whose average haul weight is 15 tons [Ref. 8].

Typically, 5 medium truck companies support a Corps. Each company is authorized sixty 5 ton tractors and one hundred and fifty 22.5 ton trailers. The transportation community anticipates an availability of 75% due to maintenance requirements [Ref. 8].

Normal convoy speeds are 32 KM per hour for hard surface roads and 16 KM per hour for cross country and loose surface roads. These speeds may seem slow, but for the reduced road trafficability typical in the TO they are quite realistic.

Each node within the WADS has an ability to receive, rewarehouse, and issue ammunition. This is called "lift capacity" (or just "lift") and is a function primarily of material handling equipment and personnel assigned. Lift capacity is a constraint on the ability of the WADS to process ammunition for inventory or movement forward.

Each CSA is operated by one or more General Support (GS) Ammunition Companies. Each GS Company has a current lift capacity of 3696 short tons (STON) per day which will be upgraded to 5332 STON per day in the future. Equal effort is usually devoted to receipt, rewarehousing, and issuing ammunition. This yields a capacity to issue 1232 STON per day and in the future 1777 STON. In high demand periods, a well stocked CSA could use its lift capacity solely toward issuing ammunition over some period of time thus increasing the ability to meet demand. However, lift is more properly thought of as a constraint on the sum of ammunition received, rewarehoused and issued. By devoting all lift toward issuing ammunition to meet a large demand, receipt of new ammunition to replenish stocks or rewarehousing of ammunition on-hand and presently not required is precluded.

A Direct Support (DS) Ammunition Company operates two ASPs which is the number usually allocated to support a forward division. The DS Company has a current lift capacity of 2172 STON per day with a future upgrade to 2732 STON per day. Under normal conditions, lift effort is divided between receipt and issue of ammunition. Simple calculations then yield, at each ASP, a capacity to issue 543 STON per day and 683 STON per day in the future. Under surge flows, each ASP could issue 1036 STON per day now and 1366 STON per day in the future until stock exhaustion, 3-5 days later. As noted before, dedicating all lift toward issuing ammunition to meet demand is at the expense of receiving additional ammunition to replenish stocks. ASPs typically do not devote much effort to rewarehousing.

The number and capacity of the ATPs varies with type of division. The table below indicates different configurations [Ref. 5 : p.2-77]

Field testing indicates the ability of the ATP to handle 600-700 STON per day for short periods of time, during high demand periods [Ref. 9]. Concept papers reviewed [Ref. 10] have projected a sustained issue of 750 STON per day for forward ATPs in the brigade area, and 1450 STON per day for the ATP in the division rear with appropriate equipment and personnel upgrades.

Table 2. DIVISION ATP DATA (F = FORWARD, M = MAIN OR REAR)

Division Type	ATP Density	Capacity per ATP
Armored Infantry Mechanized	3F	500 STON
Heavy	3F 1M	350 200 STON
Light	3F	250 STON
Airborne	3F 1M	350 500 STON
Air Assault	3F 1M	350 500 STON
Motorized	3F 1M	500 350 STON

Port and TSA capacities will vary from theater to theater. Host nation support units and GS Companies would operate the facilities in this area but lift capacities are not clear from available documents [Ref. 5 : pp. 2-60 - 2-62].

Demand for ammunition, seen at ATPs, is random. Historical data in the table below gives average consumption rates by type of division and the division's current state, in STON per day [Ref. 7 : pp. 7-5 - 7-7]:

Table 3. HISTORICAL DIVISION CONSUMPTION

Activity	Type of Division				
	Armored	Infantry	Mechanized	Airborne	Air Assault
Defense 1st Day	2432.6 STON	1896.3 STON	2156.8 STON	1373.4 STON	1825.1 STON
Successive Days	1902.8 STON	1722.0 STON	1742.3 STON	1277.9 STON	1653.1 STON
Offense 1st Day	1911.5 STON	1579.6 STON	1680.4 STON	1180.7 STON	1572.2 STON
2nd-5th Days	1424.3 STON	1350.6 STON	1295.4 STON	1018.7 STON	1297.8 STON
Successive Days	1163.4 STON	864.9 STON	1094.1 STON	552.2 STON	808.9 STON

Presuming that some sort of demand distribution exists, the above data are activity consumption means; variances are unavailable.

For many analysts, the above values are much too low and they have turned to simulations for new consumption rates [Ref. 6]. The table which follows indicates mean consumption rates for a heavy division; once again the variances are unavailable:

Table 4. SIMULATED CONSUMPTION DATA FOR HEAVY DIVISION

Agency	Consumption Rate in STON Day
Logistics Center [Ref. 1]	1558
Concepts Analysis and Combined Arms Center [Ref. 1]	2281
USAOMMCS [Ref. 1]	2589
U.S.Army-Europe [Ref. 6]	3470
Others (Upper Bound) [Ref. 11]	≤ 4545

Significant differences between historical and simulated consumption data are obvious and have caused much controversy within the Army analytic community [Ref. 6].

A detailed examination of historical and simulated data shows artillery is the major ammunition consumer comprising 65-70% of total consumption [Ref. 11] A USAOMMCS developed list [Ref. 12] indicates only 19 different ammunition types account for 91.5% of all ammunition consumed on the battlefield. Adding one more ammunition type to represent the remaining 8.5% of consumption, gives a useful 20 commodity aggregation versus explicitly modeling over 200 ammunition types regularly used. Once ammunition inventory levels (in STON) are determined then straight percentages based on the 20 major ammunition types from the USAOMMCS list will give a "rough cut" at individual stockage levels. An aggregated approach was taken versus a multicommodity flow since consumption data was in STON not individual ammunition types, ammunition is apparently consumed in roughly proportional quantities during all time periods, and the same material handling equipment and transportation assets are used to process ammunition for use. In addition, the software used limits the multicommodity flow approach except for small to moderate sized models.

B. LOCATION

The essential criterion for site selection of an ammunition facility is close proximity to an existing, all weather road. Distance to supported units or storage facilities should be minimized within security constraints. The site should be selected to facilitate smooth flow of traffic in and out once off the main road network. Also, proximity to any rail networks is always welcomed [Ref. 13].

Taking advantage of terrain masking and vegetation is key to reducing target signature since storage facilities and heavy traffic areas can be quite obvious if no effort is taken toward concealment. Location away from other likely targets is essential since ammunition facilities are likely targets themselves.

High demand units should be supported by the closest facilities. This is just common sense. Low demand units can be supported by facilities farther away but still within doctrinal limitations. However, Command and Control requirements may violate this common sense approach.

C. PROCEDURES

The Division Ammunition Officer (DAO) orders ammunition for the division based on the Commander's direction and staff guidance. The order is determined on the knowledge of upcoming operations and an anticipation of enemy action. In theory, once the DAO places an order, 8-10 hours later ammunition should arrive at the ATP in the quantity and type ordered. In contrast to civilian inventory management philosophy, an ammunition stockout is not allowed.

The DAO communicates with the Corps Material Management Center (MMC) who works closely with the Corps Movement Control Center (MCC). The MMC and MCC control and move ammunition from the Corps rear area to the brigade area [Ref. 5 : pp. 1-27 - 1-33]. The DAO's role is to "pull" flow through the network subject to MMC and MCC constraints. The proper "pull" gives the best results.

Convoys should arrive at the ATPs every 3-4 hours. The success or failure of the network depends on the DAO's ability to keep a steady flow of ammunition in the proper quantity and type to meet division needs. This depends directly on the quality of the consumption forecast sent to the MMC and MCC. If the flow is too high, excess ammunition provides an increased target signature which is an invitation for destruction. If the flow is too low, the division cannot survive.

The majority of high demand, high tonnage items flow over the CSA-ATP arcs which are 130 km in length, requiring 4-8 hours travel time. Low demand, low tonnage items flow over the ASP-ATP arcs which are 30 km long, and which require at least 1-2 hours travel time. The DAO's forecast must be as accurate as possible. The DAO cannot use the ASP as a regular source of ammunition, should his forecast be continually in error. This would eliminate any emergency source of ammunition in the event of an unanticipated enemy action. This all implies that the CSA-ATP arcs are the division's lifelines and the ASP exists primarily exists for emergency stockage.

D. DISCUSSION

The aforementioned network structure and procedures have been "tried by fire" in World War II, Korea, and Vietnam; they work. However, combat under the Airland Battle concept will place an increased demand on the system primarily due to the increased requirements on the forward units to defeat the first two enemy echelons. Natural questions that have arisen are:

1. Will the increased demand for ammunition force changes in the current system structure?
2. Are the heuristics or "rules of thumb" from past wars applicable to future conflicts?
3. What stockage policies can be used to minimize the size of ammunition facilities thereby reducing target signature?
4. What is the best placement for ammunition storage facilities to support the force?

Logically, one might question the need for the large number of storage facilities (nodes) and numerous bypass (arc) possibilities. These criticisms would be valid in a totally secure, rear area with numerous, high speed roads toward the forward areas. It is prudent to assume our adversaries, in any future conflict, will disrupt our rear areas whenever and wherever possible. Further, road networks by the very nature of war will have reduced trafficability at best and will be subject to interdiction. These two facts force a dispersion of ammunition stocks to reduce target signature and placement of stockage points as far forward as possible to minimize travel time. Redundancy in network flows and storage points is necessary to insure delivery forward should an arc or node be severed or destroyed.

E. CONCEPTUAL DIRECTIONS

USAOMMCS, in an attempt to best support the dynamic Airland Battle, is currently developing the Maneuver Oriented Ammunition Distribution System (MOADS) [Ref. 10]. The MOADS concept increases the size of the CSA, which is located in a relatively secure position, and reduces the size of the ASP, which is located in a somewhat insecure position. In addition, the number of ASPs serving a division will be increased from two to three. This will reduce target signature, increase dispersion, and provide additional redundancy. Ammunition will be supplied in Combat Configured Loads (CCLs) for high demand, high tonnage items. This will reduce consumer material handling requirements. ASP stockage will be reduced to 1-3 days of supply versus the current 3-5 days of supply. Ammunition from the CSA will be primarily CCL high tonnage, high demand items. The ASP will continue to supply non-CCL low demand, low tonnage items and emergency stockage. The new network configuration is shown in Figure 3 on page 15.

New stockage rules for each ammunition storage facility are shown below. No information on approximate physical size is available:

Table 5. MOADS STOCKAGE CRITERIA

Facility	Days of Supply
TSA	30
CSA	10
ASP	1-3
ATP	3-4 hrs.

The reduction in days of supply at the ASP will reduce the physical size which will reduce target signature, certainly a positive benefit. The tradeoff is an increased target signature for the CSA. Since the CSA is 150-160 km to the rear of the FLOT, the risk may be acceptable.

Another concept, which has been tested, is the Palletized Loading System (PLS) [Ref. 9]. This idea is best used in conjunction with MOADS. Highlights are an ability to rapidly upload and offload flatracks of ammunition pallets thereby reducing material handling and personnel requirements, conversion of ATPs to Ammunition Control Points (ACPs) that direct ammunition convoys to the unit field trains, and elimination of the TSA-ASP bypass arc. The major advantage is the rapid upload and offload of ammunition which reduces material handling requirements network-wide. This in turn increases lift capacities and thereby speeds supply to the consumers forward.

The operational complexity and manifestations of uncertainty associated with the WADS should be of real concern [Ref. 2]. Proper control by all keys players can reduce the propensity or potential of the system to crash. Without oroper control, all the proposed improvements in the WADS will be useless.

F. REMARKS

This is a brief summary of the WADS. The current "rules of thumb" based on past conflicts may not be appropriate for future wars. Analytical methods, using the current

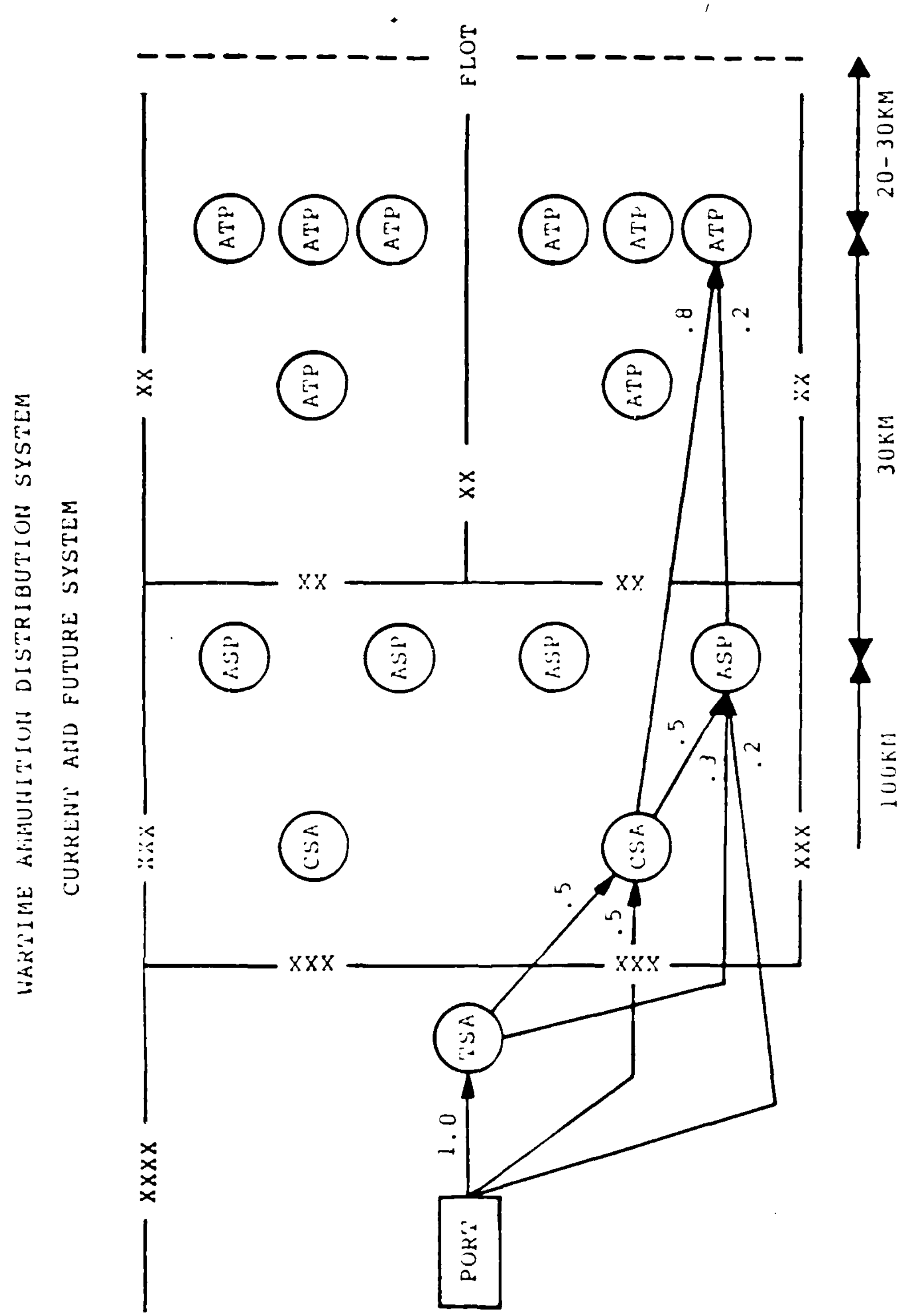

Figure 3. MOADS Wartime Ammunition Distribution System

heuristics as a starting point, can provide the means to examine the current, future, and conceptual systems through model development, formulation and solution.

III. MODEL DEVELOPMENT AND FORMULATION

Two models of the WADS are proposed within this chapter. One is an integrated optimization approach which locates facilities and determines network flows concurrently. The other is a separation heuristic which sequentially determines optimal facility location and then flow through a network to meet inventory goals and demand. Both models are coded in GAMS (Generalized Algebraic Modelling System) developed by Meeraus and and Brooke [Ref. 14] and are solved utilizing Marsten's Zero-One Optimization Methods (ZOOM) [Ref. 15] or Murtagh and Saunders' Modular In-core Non-linear Optimization System (MINOS) [Ref. 16].

A. GAMS

GAMS is a model generator and solver interface used for linear, nonlinear, and integer programming. All work for model development, formulation, and solution was obtained utilizing GAMS. The great flexiblity of GAMS is its strength. Specifically, the logical based "such that" operator, denoted by the dollar sign ($), made model development, formulation, and subsequent solutions possible. The "such that" operator is used to restrict model generation to only those constraints and variables applicable [Ref. 17]. Constraint and variable reduction made the difference between a solvable model for the following scenario and in some cases a model that could not even be formulated due to size.

B. SCENARIO

The scenario is a worst case situation in the framework of the WADS. The setting is in Korea, where after a surprise attack by the North Korean (NK) forces, we have consolidated and are now vigorously attacking toward the NK capital of Pyongyang. After a number of successful weeks of attack, we have stretched our ammunition network to the limit and must establish new ASPs and CSAs forward from their present locations. Reconnaissance elements have located a number of possible sites for the new ASPs and CSAs. As of late, NK resistance has stiffened and an armored counterattack within the next week is anticipated somewhere along the Corps' FLOT. The Corps' Commander desires the optimal location for ammunition facilities utilizing the existing road network.

In addition, the Corps' Commander wonders if the WADS structure and current operating procedures will be adequate. The MMC has acquired 30 days of demand data from another Corps' past consumption data under similar circumstances. The Corps' Commander would like an analysis of the Corps' WADS based on this data.

The Corps is composed of three Divisions abreast, in contact, and the Corps rear units which support the forward Divisions. Each Division will have 4 ATPs which gives the Corps 12 ATPs total. Each Division will be supported by 2 ASPs and 1 CSA. This means that the total Corps' requirement for ASPs is 6 and for CSAs is 3. A total of 12 possible ASP sites have been declared suitable and 4 tentative CSA locations selected. The existing road infrastructure provides the network and distances between facilities is road distance unless stated otherwise. The idea is gradually to close down the old ASPs and CSAs to the rear and open new sites forward. A graphical representation of the tactical situation is shown in Figure 4 on page 19.

The Corps' three Divisions will be composed of two Mechanized Divisions positioned on the flanks and one Armored Division in the middle. Cynics will quickly point out that mechanized/armored forces are not appropriate for the Korean theater. However, keeping in sight the goals of a generic Corps not tied to a specific theater and analyzing the structural aspects of the WADS, consistency is maintained.

C. THE INTEGRATED MODEL DEVELOPMENT

The integrated approach solves the ammunition facility location and ammunition flow problems concurrently. This is accomplished by using a generalized form of the capacitated facility location model [Ref. 18 : pp.195-197] which is a mixed integer program (MIP). The capacitated facility location model places upper bounds on the capacitates of facilities. In the problem at hand, the model places upper bounds on the ability of the ammunition storage facilities to issue, rewarehouse and receive ammunition. Upper and lower bounds are established for inventory. The doctrinal support relationships between ammunition storage facilities outlined in Chapter II and an underlying distribution network with side constraints (based on "rules of thumb" developed in past conflicts) make this problem difficult to solve. Binary variables determine ammunition facility location and support relationships between storage facilities. Continuous variables are ammunition flow from node to node and inventory from time period to time period. Binary and continuous variables interact in the constraint matrix where conditional constraints are used. If solved, the MIP gives an optimal solution with respect to

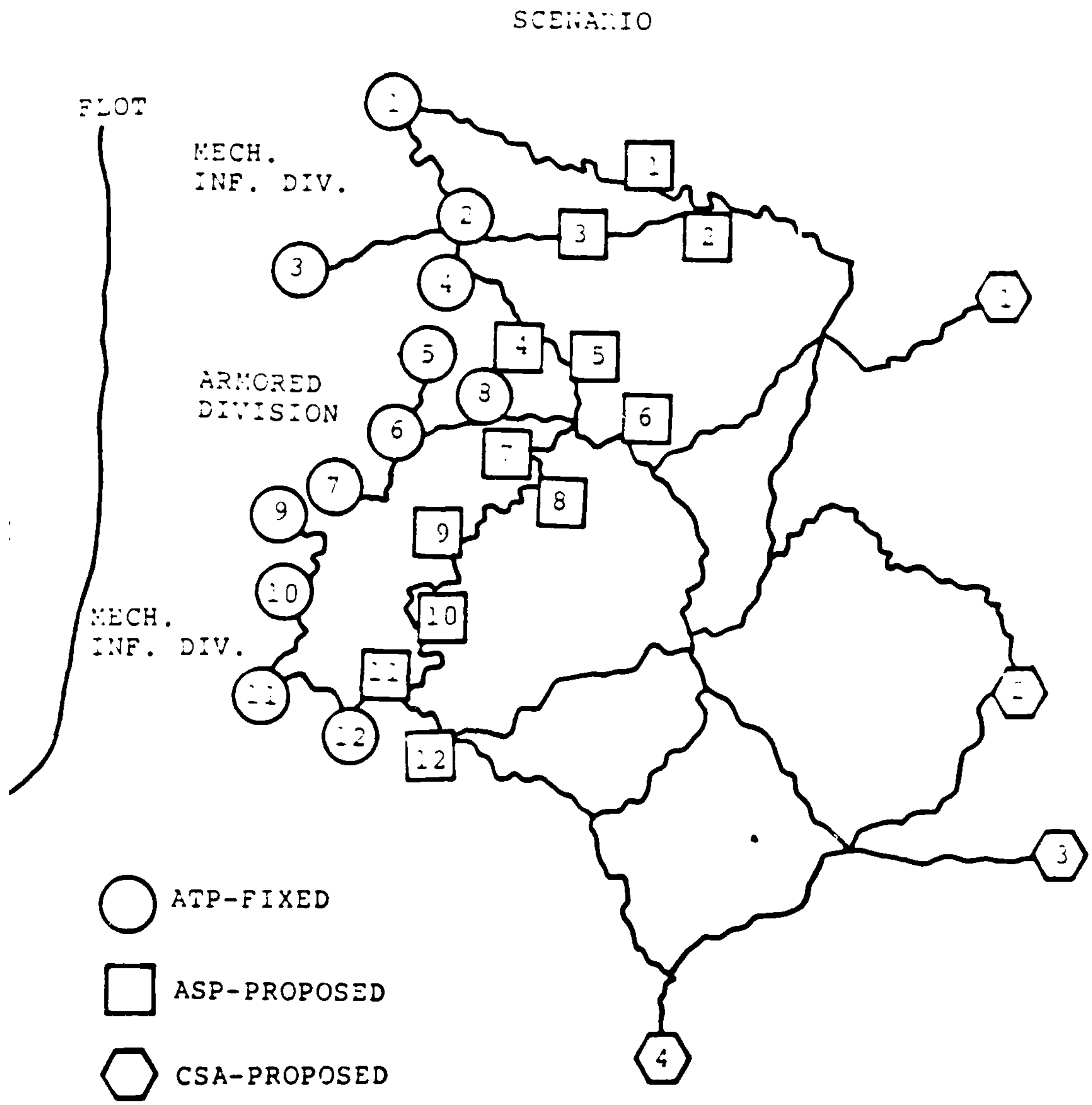

Figure 4. Scenario

facility location and network flow. This would be the most natural way to solve the scenario if computationally feasible.

D. THE INTEGRATED FORMULATION

The entire scenario is modeled as a generalized capacitated plant (ammunition storage facility) location problem which is a mixed integer program (MIP). The following formulation will open (1) or close (0) facilities using binary variables. Continuous variables are ammunition flows between facilities.

1. Indices

$i = 1,2,...,I$ (= 12) ATPs (fixed)

$j = 1,2,...,J$ (= 12) ASPs (proposed sites)

$k = 1,2,...,K$ (= 4) CSAs (proposed sites)

$t = 1,2,...,T$ (= 30) time periods

2. Data

d_{it} demand in STON/1000 at ATP i in time period t

l_{ij} distance by road from ATP i to ASP j in km

l_{jk} distance by road from ASP j to CSA k in km

l_{ik} distance by road from ATP i to CSA k in km

p_{ij} penalty cost for road quality from ATP i to ASP j

p_{jk} penalty cost for road quality from ASP j to CSA k

p_{ik} penalty cost for road quality from ATP i to CSA k

N number of ASPs per Corps (= 6)

M number of CSAs per Corps (= 3)

c_{ijt} cost to move one STON of ammunition from ASP j to ATP i in time t

c_{jkt} cost to move one STON of ammunition from CSA k to ASP j in time t

c_{ikt} cost to move one STON of ammunition from CSA k to ATP i in time t

h_{jt} cost to hold one STON of ammunition at ASP j from time t-1 to t

ML^{csa} maximum lift capacity in STON/day of the CSA (= 10664)

ML^{asp} maximum lift capacity in STON/day of the ASP (= 2732)

P^{asp} percentage of demand provided by the ASP (= 0.2)

P^{csa} percentage of demand provided by the CSA (= 0.8)

I^{up} maximum number of days of supply at the ASP (= 5)

I^{low} minimum number of days of supply at the ASP (= 1)

s_{min} minimum distance from ATP i to the FLOT in km (= 20)

s_j distance from ASP j to the FLOT in km

s_k distance from CSA k to the FLOT in km

u adjustable constant for the tactical situation (= 1)

α scaling factor for the objective function (= .01)

$\dot{v}$ number of round trips per day from CSA k to ATP i (= 3)

$\dot{r}$ number of round trips per day from CSA k to ASP j (= 4)

Γ number of tractors authorized per Corps (= 300)

$\bar{h}$ average haul weight per trailer in STON 1000 (= .015)

$\dot{a}$ tractor trailer availability on an given day (= 0.8)

P^{ammo} percentage of total tractor trailers hauling ammunition (= 0.8)

$\dot{w}$ work level at CSA issuing ammunition (= .333)

C_t cardinality of the index set t

3. Decision Variables

x_{ij} 1 if ATP i is supported by ASP j, 0 otherwise

a_{jk} 1 if ASP j is supported by CSA k, 0 otherwise

z_{ik} 1 if ATP i is supported by CSA k, 0 otherwise

y_j 1 if ASP is located at site j, 0 otherwise

b_k 1 if CSA is located at site k, 0 otherwise

f_{ijt} flow from ASP j to ATP i in time period t

f_{jkt} flow from CSA k to ASP j in time period t

f_{ikt} flow from CSA k to ATP i in time period t

I_{jt} inventory at ASP j at the end of time period t

4. Formulation (GAMS equation designations in brackets)

$$\min \sum_{i=1}^{I}\sum_{j=1}^{J}\alpha\, l_{ij}\, p_{ij}\, x_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K}\alpha\, l_{jk}\, p_{jk}\, a_{jk} + \sum_{i=1}^{I}\sum_{k=1}^{K}\alpha\, l_{ik}\, p_{ik}\, z_{ik} +$$

$$\sum_{j=1}^{J}\left(\frac{s_{\min}}{s_j}\right)^{u} y_j + \sum_{k=1}^{K}\left(\frac{s_{\min}}{s_k}\right)^{u} b_k + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} c_{ijt} f_{ijt} +$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{jkt} f_{jkt} + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} c_{ikt} f_{ikt} + \sum_{j=1}^{J}\sum_{t=1}^{T} h_{jt}\, I_{jt} \qquad (2.1)$$

[OBJFCN]

Subject To:

$$\sum_{j=1}^{J} x_{ij} = 1 \quad \forall i \tag{2.2}$$

[ONESITE (i)]

$$\sum_{i=1}^{I} x_{ij} = 2y_j \quad \forall j \tag{2.3}$$

[SERVICE (j)]

$$f_{ijt} \le ML^{asp} x_{ij} \quad \forall i, j, t \tag{2.4}$$

[BOUND1 (i, j, t)]

$$x_{ij} \le y_j \quad \forall i, j \tag{2.5}$$

[VARUPBD1 (i, j)]

$$\sum_{k=1}^{K} a_{jk} = y_j \quad \forall j \tag{2.6}$$

[HANNA (j)]

$$\sum_{j=1}^{J} a_{jk} = 2b_k \quad \forall k \tag{2.7}$$

[SUPPORT (k)]

$$f_{jkt} \le ML^{asp} a_{jk} \quad \forall j, k, t \tag{2.8}$$

[BOUND2 (j, k, t)]

$$a_{jk} \le b_k \quad \forall j, k \tag{2.9}$$

[VARUPBD2 (j, k)]

$$\sum_{k=1}^{K} z_{ik} = 1 \quad \forall i \tag{2.10}$$

[SINGLE (i)]

$$\sum_{i=1}^{I} z_{ik} = 4b_k \quad \forall k \tag{2.11}$$

[HELP (k)]

$$f_{ikt} \leq ML^{csa} z_{ik} \quad \forall i, k, t \tag{2.12}$$

[BOUND3 (i, k, t)]

$$z_{ik} \leq b_k \quad \forall i, k \tag{2.13}$$

[VARUPBD3 (i, k)]

$$\sum_{j=1}^{J} y_j = N \tag{2.14}$$

[LIMIT]

$$\sum_{k=1}^{K} b_k = M \tag{2.15}$$

[CEILING]

$$-\sum_{k=1}^{K} f_{jkt} + \sum_{i=1}^{I} f_{ijt} - I_{j\,t-1} + I_{jt} = 0 \quad \forall j, t \tag{2.16}$$

[BALASP (j, t)]

$$-\sum_{j=1}^{J} f_{ijt} - \sum_{k=1}^{K} f_{ikt} = -d_{it} \quad \forall i, t \tag{2.17}$$

[BALATP (i, t)]

$$\sum_{j=1}^{J} f_{jkt} + \sum_{i=1}^{I} f_{ikt} \le ML^{csa} b_k \quad \forall k, t \tag{2.18}$$

[CAPCSA (k, t)]

$$\sum_{k=1}^{K} f_{jkt} + \sum_{i=1}^{I} f_{ijt} \le ML^{asp} y_j \quad \forall j, t \tag{2.19}$$

[CAPASP (j, t)]

$$\sum_{j=1}^{J} \sum_{t=1}^{T} f_{jkt} + \sum_{i=1}^{I} \sum_{t=1}^{T} f_{ikt} \le \hat{w}\, C_t\, ML^{csa}\, b_k \quad \forall k \tag{2.20}$$

[STABLE (k)]

$$\sum_{j=1}^{J} \sum_{k=1}^{K} \frac{f_{jkt}}{\dot{v}} + \sum_{i=1}^{I} \sum_{k=1}^{K} \frac{f_{ikt}}{\dot{r}} \le T\, \bar{h}\, \dot{a}\, P^{ammo} \quad \forall t \tag{2.21}$$

[TRANS (t)]

$$I^{low} \sum_{i=1}^{I} d_{i\,t+1}\, x_{ij} \le I_{jt} \le I^{up} \sum_{i=1}^{I} d_{i\,t+1}\, x_{ij} \quad \forall j,\ t = 1, 2, \ldots, T-1 \tag{2.22}$$

[LOWER and UPPER (j, t)]

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{t=1}^{T} f_{ikt} = P^{csa} \sum_{i=1}^{I} \sum_{t=1}^{T} d_{it} \tag{2.23}$$

[LONGRUN]

$$f_{jkt}, f_{ijt}, f_{ikt}, I_{jt} \geq 0 \tag{2.24}$$

$$x_{ij}, a_{jk}, z_{ik}, y_j, b_k \in \{0,1\} \tag{2.25}$$

The GAMS code for the MIP follows in Appendix A.

Decision variables, x_{ij} and a_{jk}, establish a support relationship so ammunition may flow from CSA k through ASP j to ATP i. Decision variable z_{ik} allows ammunition to flow on the bypass arc from CSA k to ATP i.

The objective function, equation 2.1, is composed of two parts, one for locating the ammunition facilities and the other for flow of ammunition.

Lengths l_{ij}, l_{jk}, and l_{ik}, and penalty costs p_{ij}, p_{jk}, and p_{ik}, form the basis for one portion of the objective function. Essentially, the penalty costs make road distance longer for use of substandard roads (arcs). In particular, a cost of 1.00 is given to two lane roads, 2.00 for one lane roads, and 4.00 for trails. For composite roads, a linear combination is used.

To fix a cost for direct distance from the FLOT to the ATPs, proximity costs were established utilizing a convex cost function $(\frac{s_{min}}{s_j})^u$ and $(\frac{s_{min}}{s_k})^u$ where s_{min} is minimum distance from the ATP to the flot. The values s_j and s_k are the straight line distances from the ASP and CSA to FLOT. Multiplying by s_i scales the convex function in terms of the ATP and u is an adjustable parameter which may vary with the tactical situation. As the distance to the FLOT decreases, the cost increases which will discourage placement of an ASP or CSA too far forward where it might be destroyed. This portion of the objective function forms the fixed costs for placing an ASP at site j and placing a CSA at site k.

The trade-off between length modified by a road penalty cost and the convex function based proximity cost "drive" the location portion of the objective function. The modified length portion minimizes distance from facility to facility and has a tendency to "pull" the ASPs and CSAs toward the FLOT. The fixed proximity costs "push" the ASPs and CSAs away from the FLOT. The adjustable scalar α regulates the amount of "push" and "pull."

The flow portion of the objective function is straightforward. Costs per unit c_{ijt}, c_{jkt}, and c_{ikt} are charged for moving ammunition while h_{jt} is charged for holding each unit of ammunition. These costs are subjective and are determined by the user. For instance, the costs might be thought of a risk and therefore would change with the battlefield situation and time.

Many of these constraints are conditioned on whether a ammunition storage facility is open closed or support relationship between storage facilities is established not established. If an ammunition facility is open or support relationship established, the following constraints are "turned on": 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.11, 2.12, 2.13, 2.18, 2.19, 2.20 and 2.22. Otherwise, when the ammunition storage facility is closed or the support relationship not established, the aforementioned constraints left hand side and right hand side are set to zero.

The description of each constraint, below, is the result of doctrine or required to formulate a solvable model. Upper bounds on lift capacity for the CSAs and ASPs as well as upper and lower bounds for inventory are outlined in Chapter II. Constraint 2.2 specifies only one support path from ATP i to ASP j may exist for each ATP i. Constraint 2.3 forces ASP j to support two ATPs, if opened. Constraint 2.6 establishes a unique support relationship between CSA k and ASP j, if opened. Constraint 2.7 mandates CSA k, if opened, to support two ASPs. Constraint 2.10 specifies that only one CSA k may support a given ATP i. Constraint 2.11 requires a CSA, if opened, to support four ATPs. Constraints 2.14 and 2.15 set the Corps authorization for ASPs and CSAs respectively. Constraints 2.16 and 2.17 are flow balance equations for the ASP and ATP: ammunition flow in must equal flow out. Constraint 2.18 requires all flow out of CSA k to ASP j or ATP i, not to exceed its lift capacity. Constraint 2.19 insures that the amount of ammunition received and issued by the ASP does not exceed the established lift capacity. Constraint 2.20 sets the upper and lower bounds for inventory at any ASP, if opened. Constraint 2.21 establishes a long run upper bound of 33% on the amount of lift capacity that a CSA may devoted to issuing ammunition. This is a realistic requirement since a CSA must devote lift effort not only to issuing ammunition but receiving new ammunition and rewarehousing ammunition on-hand. Corps transportation assets form the basis for constraint 2.22. Essentially, flows out of all CSAs to each ASP and ATP, divided by round trips possible per day, must be less than available transportation (degraded by maintenance and mission factors) times average haul weight per trailer. By doctrine, Corps transportation assets move ammunition from the CSAs to the ASPs and ATPs. Division transportation assets move ammunition from the ASPs to the ATPs. Finally, constraint 2.23 supports doctrine, which requires the majority of ammunition supplied to an ATP to come from the CSA on bypass arcs.

Constraints 2.4, 2.5, 2.8, 2.9, 2.12, and 2.13 are called variable upper bounds (VUBs) by Schrage [Ref. 18 : pp.193-195]. The VUBs create a much tighter formulation of the MIP, often resulting in natural integer solutions [Ref. 19 : pp.61-68]. Constraints 2.5, 2.9, and 2.13, in the context of this scenario, state that if ASP j or CSA k are not open then no support paths x_{ijk}, a_{ik}, z_{ik} are possible. Constraint 2.4 allows a flow of ammunition from ASP j to ATP i, if opened, and establishes an upper bound on flow given by the lift capacity of the ASP during time period t. Constraint 2.8 allows flow from CSA k to ASP j if a support relationship is established and once again sets an upper bound on flow. The lift capacity of the ASP is used to bound flow since ammunition flowing from CSA k to ASP j during time period t must not exceed the capability of the ASP to receive that flow. Constraint 2.12 sets an upper limit of flow on the bypass arcs if a support relationship exists between CSA k and ATP i. Lift capacity of the CSA sets the upper bound on flow to ATP i in time period t. This simple, yet elegant concept of the VUBs is extremely powerful as it often avoids the requirement for branch and bound, cuts, or a heuristic to arrive at an integer solution [Ref. 18 : pp.193-195]. The drawback is the large number of constraints generated which increases with index size, i.e $x_{ijk} \leq y_j$ has $I \times J \times K$ constraints. Since optimal integer solutions for the MIP are difficult to obtain without the VUBs, the computational burden they impose must be borne [Ref. 19 : pp.61-68].

The power of the GAMS modelling language is easily seen as thousands of constraints are generated with only 42 equation generation commands! The amount of effort required to formulate this model in say LINDO [Ref. 18] would be significantly greater.

The integrated formulation, although mathematically correct, is not able to arrive at feasible solutions (in a reasonable period of time) for the problem at hand. Therefore, another approach is required.

E. THE SEQUENTIAL HEURISTIC DEVELOPMENT

Because full-scale solutions to the MIP proved to be impractical, a sequential heuristic was developed which separates the problem into one of first locating ammunition facilities and then establishing valid flows between these facilities. The heuristic takes advantage of a sequential solving procedure available to GAMS and also follows the principal of only entering data once.

Part one of the heuristic is a facility location problem. This problem is modeled as a binary integer program (BIP) known in the literature as the uncapacitated plant location model [Ref. 18 : pp.193-195] or the m-median problem [Ref. 19 : pp.58-60]. This

BIP can be extended to optimally locate ammunition storage facilities in accordance with criteria outlined in Chapter II.

Part two of the scenario can be modeled as a minimum cost network flow problem, specifically a production-transportation-inventory (PTI) model [Ref. 20]. In this scenario production will be called supply and a supply of ammunition will flow through the network. In its simplest form, the PTI model is a pure network. However, due to doctrinal restrictions, side constraints exist that cannot be eliminated. This is key since with a pure network, specialized solvers, such as GNET [Ref. 21], could be used to determine optimal flow. Unfortunately the network's side constraints preclude the use of GNET and GAMS' LP solver is utilized instead. Solution times will be slower than a specialized solver but still acceptable.

Solving the BIP and PTI models in succession through a GAMS sequential solving technique allows the development of a heuristic that separates the problem into 2 small submodels. The BIP is solved and facility solution decisions passed to the PTI model to determine flows.

F. THE SEQUENTIAL HEURISTIC FORMULATION

The sequential formulation differs not only in the separation technique used but in the relationship between binary (location) and continuous (flow) variables. In the MIP, location and flows are related together in the constraint matrix. In the sequential heuristic, this relationship is reflected only in the objective function of the BIP by a demand term (which must be satisfied by flow). The BIP contains only binary variables. The PTI uses continuous variables.

Briefly, the facility location problem is solved to determine those ASPs and CSAs opened and support relationships. Next, the binary data is molded into "such that" operators which eliminate network constraints that are not applicable. Finally, a small network flow model is solved resulting in flows necessary to meet inventory goals at the ASPs and demand at the ATPs.

The sequential heuristic is formulated as follows:

1. **Indices (same as MIP)**
2. **Data (same as MIP)**
3. **Binary Decision Variables for the BIP**

x_{ijk} 1 if ATP i is supported by ASP j which is supported by CSA k, 0 otherwise

z_{ik} 1 if ATP i is supported by CSA k, 0 otherwise

y_j 1 if ASP is located at site j, 0 otherwise

b_k 1 if CSA is located at site k, 0 otherwise

4. Continuous Decision Variables for the PTI

f_{jit} flow from ASP j to AIP i in time period t

f_{kjt} flow from CSA k to ASP j in time period t

f_{kit} flow from CSA k to AIP i in time period t

I_{jt} inventory at ASP j at the end of time period t

5. Formulation (GAMS equation designations in brackets)

The first module is the uncapacitated facility location problem which is a BIP

$$\min \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{t=1}^{T} [\alpha\, l_{ij}\, p_{ij} + \alpha\, l_{jk}\, p_{jk}]\, P^{asp}\, d_{it}\, x_{ijk} +$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{t=1}^{T} \alpha\, l_{ik}\, p_{ik}\, P^{csa}\, d_{it}\, z_{ik} + \sum_{j=1}^{J} \left(\frac{S_{min}}{S_j} \right)^{\beta} y_j + \sum_{k=1}^{K} \left(\frac{S_{min}}{S_k} \right)^{\beta} b_k \tag{2.26}$$

[OBJFCN]

Subject To:

$$\sum_{j=1}^{J} \sum_{k=1}^{K} x_{ijk} = 1 \quad \forall i \tag{2.27}$$

[ONESITE (i)]

$$\sum_{i=1}^{I} \sum_{k=1}^{K} x_{ijk} = 2y_j \quad \forall j \tag{2.28}$$

[SERVICE (j)]

$$\sum_{i=1}^{I} \sum_{j=1}^{J} x_{ijk} = 4b_k \quad \forall k \tag{2.29}$$

[SUPPORT (k)]

$$x_{ijk} \leq y_j \quad \forall i, j, k \tag{2.30}$$

[VARUPBD1 (i, j, k)]

$$x_{ijk} \leq b_k \quad \forall i, j, k \tag{2.31}$$

[VARUPBD2 (i, j, k)]

$$\sum_{k=1}^{K} z_{ik} = 1 \quad \forall i \tag{2.32}$$

[SINGLE (i)]

$$\sum_{i=1}^{I} z_{ik} = 4b_k \quad \forall k \tag{2.33}$$

[HELP (k)]

$$z_{ik} \leq b_k \quad \forall i, k \tag{2.34}$$

[VARUPBD3 (i, k)]

$$\sum_{j=1}^{J} y_j = N \tag{2.35}$$

[LIMIT]

$$\sum_{k=1}^{K} b_k = M \tag{2.36}$$

[CEILING]

$$x_{ijk}, z_{ik}, y_j, b_k \in \{0,1\} \tag{2.37}$$

The binary solution data is now passed to form "such that" operators for the second module. The "such that" operator (S) forms the following sets:

J' = ASPs which are open.

K' = CSAs which are open.

$L(I, J')$ = ASP j supports ATP i

$L(J', K')$ = CSA k supports ASP j

$L(I, K')$ = CSA k supports ATP i

The network flow model (PTI) is now formulated with doctrinal side constraints over the sets defined above:

$$\min \sum_{(i,j)\in L(I,J')} \sum_{t=1}^{T} c_{ijt} f_{ijt} + \sum_{(j,k)\in L(J',K')} \sum_{t=1}^{T} c_{jkt} f_{jkt} +$$

[NOBJFCN]

$$\sum_{(i,k)\in L(I,K')} \sum_{t=1}^{T} c_{ikt} f_{ikt} + \sum_{j\in J'} \sum_{t=1}^{T} h_{jt} I_{jt} \tag{2.38}$$

Subject To:

$$-\sum_{(j,k)\in L(J',K')} f_{jkt} + \sum_{(i,j)\in L(I,J')} f_{ijt} - I_{j\,t-1} + I_{jt} = 0 \quad \forall j \in J', t \tag{2.39}$$

[BALASP (j, t)]

$$-\sum_{(i,j)\in L(I,J')} f_{ijt} - \sum_{(i,k)\in L(I,K')} f_{ikt} = -d_{it} \quad \forall i, t \tag{2.40}$$

[BALATP (i, t)]

$$\sum_{(j,k)\in L(J',K')} f_{jkt} + \sum_{(i,k)\in L(I,K')} f_{ikt} \le ML^{csa} \quad \forall k \in K', t \tag{2.41}$$

[CAPCSA (k, t)]

$$\sum_{(j,k)\in L(J',K')} f_{jkt} + \sum_{(i,j)\in L(I,J')} f_{ijt} \le ML^{asp} \quad \forall j \in J', t \tag{2.42}$$

[CAPASP (j, t)]

$$\sum_{(j,k)\in L(J',K')} \sum_{t=1}^{T} f_{jkt} + \sum_{(i,k)\in L(I,K')} \sum_{t=1}^{T} f_{ikt} \le \hat{w}\, C_t\, ML^{csa} \quad \forall k \in K' \tag{2.43}$$

[STABLE (k)]

$$\sum_{(j,k)\in L(J',K')} \frac{f_{jkt}}{\dot{v}} + \sum_{(i,k)\in L(I,K')} \frac{f_{ikt}}{\dot{r}} \le T\, \bar{h}\, \dot{a}\, P^{ammo} \quad \forall t \tag{2.44}$$

[TRANS (t)]

$$\sum_{(i,k)\in(I,K')} \sum_{t=1}^{T} f_{ikt} = P^{csa} \sum_{i=1}^{I} \sum_{t=1}^{T} d_{it} \tag{2.45}$$

[LONGRUN]

$$I^{low} \sum_{i=1}^{I} d_{i\,t+1} \le I_{jt} \le I^{up} \sum_{i=1}^{I} d_{i\,t+1} \quad \forall j \in J',\ t = 1,2,\ldots,T-1 \tag{2.46}$$

[Defined in Variable Declaration]

$$f_{jkt}, f_{ijt}, f_{ikt}, I_{jt} \ge 0 \tag{2.47}$$

The GAMS code for the sequential heuristic follows in Appendix B.

The sequential heuristic formulation is quite similar to the MIP. In fact, many of the same constraints are used. The major difference is the decision variable x_{ijk} instead of x_{ij} and a_{jk}. The variable x_{ijk} establishes a single support path from the CSA k through ASP j to ATP i versus two paths with decision variables x_{ij} and a_{jk}.

The objective function's structure for the first module is different from the location portion of the MIP. Here a trade-off between demand and length modified by a road penalty is created. Those ATPs with higher demands aggregated over T time periods will be supported by the ASPs and CSAs which are the closest. Those ATPs with less demand over T time periods will be supported by ammunition facilities farther away. Since the majority of demand is supplied over the CSA-ATP arcs, demand is weighted by the long term bypass goal (80%) for the CSA positioning. ASP location is determined by the remaining weighted demand. Incorporating demand in the objective function is necessary for the sequential heuristic since flow, inventory and location variables do not interact in the constraint matrix.The decomposition technique separates location from flow and inventory.

Constraints 2.27 through 2.37 generate the constraint matrix for the first module, an uncapacitated facility location problem, a BIP. Constraint 2.27 specifies only one *ijk* support path may be established to ATP *i*. Constraint 2.28 forces ASP *j* to support two ATPs *i*. Constraint 2.29 allows for two ASPs *j* to be directly supported by CSA *k* and four ATPs *i* indirectly. Constraint 2.32 establishes only one *ik* bypass from CSA *k* to ATP *i*. Constraint 2.33 mandates CSA *k* to support four ATPs *i* directly. Constraints 2.35 and 2.36 set the Corps authorization for ASPs and CSAs respectively. Constraints 2.30, 2.31 and 2.34 are VUBS.

After solving the BIP, the binary data which establishes support relationships and those ASPs and CSAs opened is passed through an error check. If no errors are detected, then "such that" operators are coded to generate the exact number of constraints necessary. For the problem at hand, over 70,000 are possible. Logical variable and constraint elimination resulted in over a 98% reduction to 1332 constraints, well within the scope that ZOOM or MINOS can solve [Ref. 14 : Ch.18 pp.3-4].

The objective function for the second module is exactly the same as the flow portion of the MIP, i.e., cost to move and cost to hold. Constraints are similar except that only constraints corresponding to the open facilities in the BIP solution are allowed. Constraints 2.39 and 2.40 are flow balance constraints for the ASPs and ATPs respectively. Constraints 2.41, 2.42, 2.43, 2.44 and 2.45 disrupt the pure network flow. Constraints 2.41 and 2.42 capacitate the the CSAs and ASPs. Constraint 2.43 sets a long term goal on percentage of lift capacity devoted to issuing ammunition. Constraint 2.44 insures flow does not exceed transportation capabilities and constraint 2.45 establishes doctrinal bypass requirements. Constraint 2.46 provides an upper and lower bound for the inventory at ASP *j*. By doctrine, a required number of days of supply are to be on-hand for each ATP an ASP supports.

G. TRANSPORTATION

Required transportation assets to support ammunition flow are determined at the end of each GAMS formulation. Ammunition flows are constrained by available transportation assets which are degraded and aided by the factors discussed in Chapter II.

Constraint 2.21 in the MIP and constraint 2.44 in the sequential heuristic restrict ammunition flows from CSA k to ASP j and ATP i in accordance with number of tractor trailers available, average haul weight per 22.5 ton trailer, availability due to maintenance requirements and percentage of Corps transportation assets dedicated to moving ammunition forward. Ammunition flows between storage facilities are divided by number of round trips possible per day which levels out flow over a 24 hour period. The number of 5 ton tractors and 22.5 ton trailers needed is calculated by dividing the restricted flows with an average haul weight of 15 STON. A rough transportation plan is then obtained which gives the required number of tractor trailers for each set of arcs to move ammunition forward to meet inventory goals and demand. This estimate is no doubt optimistic since it assumes that tractor trailers are an infinitely divisible resource. An argument could be made to include a relocation factor in the right-hand-side of constraints 2.21 and 2.44 to account for the optimism in calculations.

IV. COMPUTATIONAL EXPERIENCE AND SOLUTIONS

This chapter presents computational results and scenario solutions. Implementation of the MIP formulation and results for a 3 time period problem are discussed. Results for the sequential heuristic are then reported and a comparison of both the integrated and sequential approaches is given. Finally, the chapter is closed with comments concerning the utilization of GAMS for modelling the WADS.

A. THE MIP

The MIP for the given 30 time period scenario could not be formulated on the computer due to the size of the problem. The only option before abandoning the MIP in favor of the sequential heuristic was to reduce the number of time periods until the problem was small enough. A reduction from 30 time periods to 3 time periods was required before a formulation and solution could be obtained.

Using an IBM 3033 AP for a 3 time period formulation of the MIP, ZOOM requires 86.6 CPU seconds to arrive at an optimal solution. The LP relaxation of the MIP gives an integer solution.

For the sake of comparison, the sequential heuristic was formulated for 3 time periods. Using ZOOM for the first module and MINOS for the second module resulted in solution times of 16.9 CPU seconds for the ammunition facility location model and 0.5 CPU seconds for the network flow model. This yields a total of 17.4 CPU seconds, roughly 5 times faster than the MIP!

The solution values for the MIP and sequential heuristic differ in ASPs opened. The MIP gives the best solutions if it can be solved. Solution times and the size of problems that can be solved certainly favor the sequential heuristic. However, an examination of solution quality is necessary to fully justify general use of sequential heuristic for analysis.

By fixing the ASP and CSA open/close values at solution levels given by the sequential heuristic and forcing those values into the MIP, the quality of solutions can be measured by the change in the objective function value. A small change in objective function value would indicate that the sequential heuristic solutions are "good" and would justify use in the following analysis.

The objective value of the 3 time period MIP from a "cold start" is 81.75. The LP relaxation gives an integer solution. Using the ASP and CSA open/close solution values from the sequential heuristic as a partial, starting, feasible solution yields an optimal objective value of 83.43 which is 2% from the optimal integer solution and the lower bound.

Another comparison for a 5 time period problem provides further justification for use of the sequential heuristic. As previously discussed the MIP for 5 time periods could not be formulated and solved. However, solving the LP relaxation of the 5 time period problem with MINOS gives a lower bound of 121.09. Then, using the sequential heuristic's ASP and CSA open close solutions as a starting feasible solution as before, the 5 time period MIP can be solved in 64.5 CPU seconds with an objective function value of 121.25. This objective function value is .13% from the lower bound.

The aforementioned examples imply that the sequential heuristic's solutions are "good" enough for analysis particularly when coupled with much faster solutions times and the capability to handle much larger problem size. The integer portion of the sequential heuristic gives solutions which are "close" to the actual integer solutions provided by the MIP and "close" to the lower bound given by solving the LP relaxation. In general, the sequential heuristic does not guarantee optimal solutions, only "good" ones [Ref. 22].

Since the MIP could not be formulated and solved for the given scenario, all further analysis was pursued using the sequential heuristic. Forecasting 30 days of ammunition is probably unrealistic. However, Corps' planning staffs certainly forecast farther ahead than three days, something on the order of two weeks. The main point is that a tool is presented for warplanning and actual logistic implementation. The sequential heuristic is not confined to 3 time periods. If 3 time periods are appropriate or under some circumstance applicable, a more rapid solution time is achieved using the heuristic versus the MIP.

Solutions for the 3 time period MIP indicate a shortage in lift capacity at the CSA and ASP and a reluctance to carry inventory from time period to time period. To obtain a feasible solutions, CSA lift capacity was increased to 10664 STON per day, ASP lift capacity increased to 2732 STON per day and the lower bound for inventory at the ASP reduced to one day of supply. In addition, 80% of the authorized tractor trailers were required as well as an 80% maintenance availability. These results are similar to those discovered using the sequential heuristic, so an extended discussion is delayed.

B. THE SEQUENTIAL HEURISTIC

Following the doctrinal guidelines of Chapter II, appropriate parameters and scalars were entered into the GAMS code of Appendix A for 30 time periods and executed.

The sequential heuristic requires 21.9 CPU seconds to arrive at optimality. The ammunition facility location model is solved in 7.4 CPU seconds using ZOOM. MINOS solves the network flow model in 14.5 CPU seconds. A combined solution time of 21.9 CPU seconds with less than 2 megabytes of computer memory is credited to the "such that" operator. Constraint and variable reduction yields 1861 binary variables, 487 constraints and a sparsity of 1.46% for the first module; 5215 continuous variables, 845 constraints and sparsity of 0.57% for the second module. This is significant since early attempts at model formulation would have generated a combined total of over 70,000 constraints!

By doctrine, using bypass percentages of 80% from the CSA to the ATP, lift capacities of 5332 STON per day for the CSA and 1366 STON per day for the ASP, an inventory goal of 3-5 days of supply at the ASP, 75% for maintenance availability and 75% of Corps tractor trailers dedicated to hauling ammunition, no feasible solution exists. Evidently, with increased consumption rates furnished by USAOMMCS (the results simulating an Airland Battle scenario), increased demand and inventory goals cannot be supported by the existing or proposed WADS.

Assuming that inventory can be sacrificed to meet demand, adjustments to goals were analyzed. Reducing the inventory goal's lower bound of 3 days of supply at the ASP to a lower bound of 1 day of supply decreases the number of infeasibilities substantially but not completely. The heuristic indicates that whenever possible the minimum inventory will be held reducing tactical costs in the objective function. Since the scenario demand has abrupt "jumps", enough inventory to meet the minimum requirements for the first and succeeding days of high consumption will be carried forward. Otherwise, minimum inventory is carried or the model is "bleeding off" inventory to get to a minimum level.

By doctrine, one or more GS companies operate at the CSA. So the next step toward achieving a feasible solution was to increase lift capacity at the CSA by a factor of two to 10664 STON per day. This resulted in another drop in the number of infeasible constraints. Finally, an increase in ASP lift capacity to 2732 STON per day gave an optimal solution.

The aforementioned adjustments to achieve optimality are a long way from the "rules of thumb" developed in past conflicts and published in current Army Field Manuals. The important question to ask is, "Are simulated consumption rates an accurate representation of reality?" If not, what is? This is a question for the Army analytic community and one of much controversy as previously mentioned.

When optimal, feasible solutions were obtained from the sequential heuristic, the model's flow and inventory behavior were examined.

After an inventory level is set at ASP j, the f_{kt} flows build the inventory. When inventory levels become too high, for the following period's stockage level, the f_{t} flows "bleed" inventory off. The f_{kt} bypass flow satisfies the majority of the demand and, if allowed, will meet all demand requirements eliminating the need for f_{jkt} and f_{ijt} flows and I_t inventory. Since there is a positive cost associated with holding inventory, the model attempts to reduce inventory to the minimum levels possible. The inventory goal's lower bound forces this minimum level above zero. Prior to and during periods of high demand, limited lift and limited transportation assets can force inventory levels above the lower bound. This model behavior can be contrasted with a stochastic inventory model which would hold inventory for a specific purpose such as to avoid a stockout situation.

The heuristic's tendency is to carry the minimum inventory possible. Inventory levels hover close to the lower bound and only exceed that lower bound immediately prior to, during, or after a high demand period. When excess inventory is on-hand because the consumption level has decreased, the model will reduce inventory levels by meeting demand with the excess ammunition using the f_{ijt} flows.

Varying bypass percentages gives some interesting results. As more demand is met utilizing the CSA-ATP arcs, less capability is present to build and "bleed off" inventory. At 90% bypass flow, the model tends to build and hold inventory at levels slightly higher than at levels determined with a doctrinal 80% level. As less demand is met over the bypass arcs, the capability to increase and draw down inventory increases. 75% bypass flow will hold inventory at a level very close to the minimum requirement or in a rapid draw down to achieve a minimum level. If the requirement of inventory goals is loosened, then this characteristic is not observed; the model will not carry inventory. If an inventory goal is set and adhered too, then high bypass percentages hold slightly higher inventory than lower bypass percentages.

Ideally, the WADS would only be composed of CSAs and ATPs. If precise forecasting, sufficient transportation, and steady, predictable enemy activity could be guaranteed, no inventory would be necessary. Ammunition would arrive just in time for use. However, this digression is not realistic. Ammunition will be stocked at the ASP since unforecasted requirements are an operational fact and as previously mentioned stockouts are fatal. Inventory provides a level of security or buffer against unanticipated requirements.

The WADS requires all demand at the ATPs to be satisfied and inventory goals at the ASPs to be met. If the majority of demand is supplied over the set of CSA-ATP arcs, a reduced capability is left to build inventory to required levels. This is seen during brief high demand periods. Insuring sufficient inventory in accordance with Army doctrine, requires larger inventories carried from period to period or a decrease in the amount of demand satisfied on the bypass arcs. In a period of high demand, meeting a large portion of the demand over the CSA-ATP arcs and meeting doctrinal inventory levels may cause a shortfall in CSA lift capacity. When little lift capacity is available to build inventories, larger inventories are carried forward with each time period. Carrying minimum levels of inventory at the ASP allows only limited recourse in an emergency situation. So a trade-off exists; the WADS can either meet the majority of demand over the bypass arcs or meet the doctrinal goals for inventory.

There are no easy answers. The model is feasible with 1 day of supply at the ASP and an 80% bypass requirement. This is certainly not a great deal of security should inventory levels be at a minimum. For the demand data given, the only recourse is to provide an increased lift capability at the CSAs and ASPs to overcome inventory shortages and insure sufficient transportation assets to move the ammunition where needed.

C. TRANSPORTATION

An analysis of the transportation calculations indicates a probable shortfall under periods of high demand depending on tractor trailer availability and the amount of Corps transportation assets dedicated to hauling ammunition forward. Assuming that Corps tractor authorization does not change and using the 15 STON planning figure for average haul weight of the 22.5 ton trailers, the parameters that can vary are availability $\dot{a}$ and dedicated assets P^{ammo} which are related multiplicatively in the right-hand-side of either formulation. Provided that $\dot{a}\, P^{ammo} \geq .543$ the model will remain feasible. As this product approaches .543, the model carries more inventory. This translates into, as less transportation is available due to maintenance requirements or lack of dedicated assets, more inventory must be carried from time period to time period to meet inventory goals and demand. The model uses the shorter trips between the CSA and ASP as a more efficient use of transportation to build inventory for later demands rather the longer CSA to ATP trips which immediately satisfy demand. As the product moves away from .543 less inventory is carried forward. These calculations are not exact since individual types of ammunition sometimes "cube out" before they weigh out. The reverse is also true. This makes the 15 STON average haul weight suspect in some situations. However, 15 STON of ammunition per tractor trailer is the given planning figure. In addition, any number of vehicles could be used to haul ammunition in an emergency. Impressed vehicles would be taken away from their primary tasks moving soldiers, supplies other than ammunition, etc. However, assuming the authorized transport assets as outlined in Chapter II are on-hand, transportation could be short under heavy demand without proper management by the MCC.

D. SCENARIO SOLUTION

After execution of the sequential heuristic with the given data, the following recommendations are presented to the Corps' Commander:

1. Location

Open ASPs at sites 4, 5, 6, 7, 11, and 12 (Figure 5 on page 41).

Open CSAs at sites 1, 2, and 4 (Figure 5 on page 41).

2. Flow

Maintain 1-5 days of supply at each ASP.

Each ASP must be operated by one DS Company instead of the usual one DS Company per two ASPs.

Each CSA must be operated by two GS Companies.

Bypass flow should be 75% for more control over inventory.

Corps' transportation assets are marginal during high demand periods. The product of availability and dedicated assets must be greater than 0.543 for the Corps WADS to function properly.

Some ATPs will exceed lift capability and require augmentation for sustained operations.

Accurate forecasting by the DAOs is critical to successful support of the forward brigades.

The Corps' Commander, in turn, could issue the above guidance to the planning staff for study. The constraints used to arrive at an optimal solution may not actually be tight. Some slack in the form of additional assets may exist which could loosen the formulation and make implementation easier. However, this would require another

SCENARIO SOLUTION

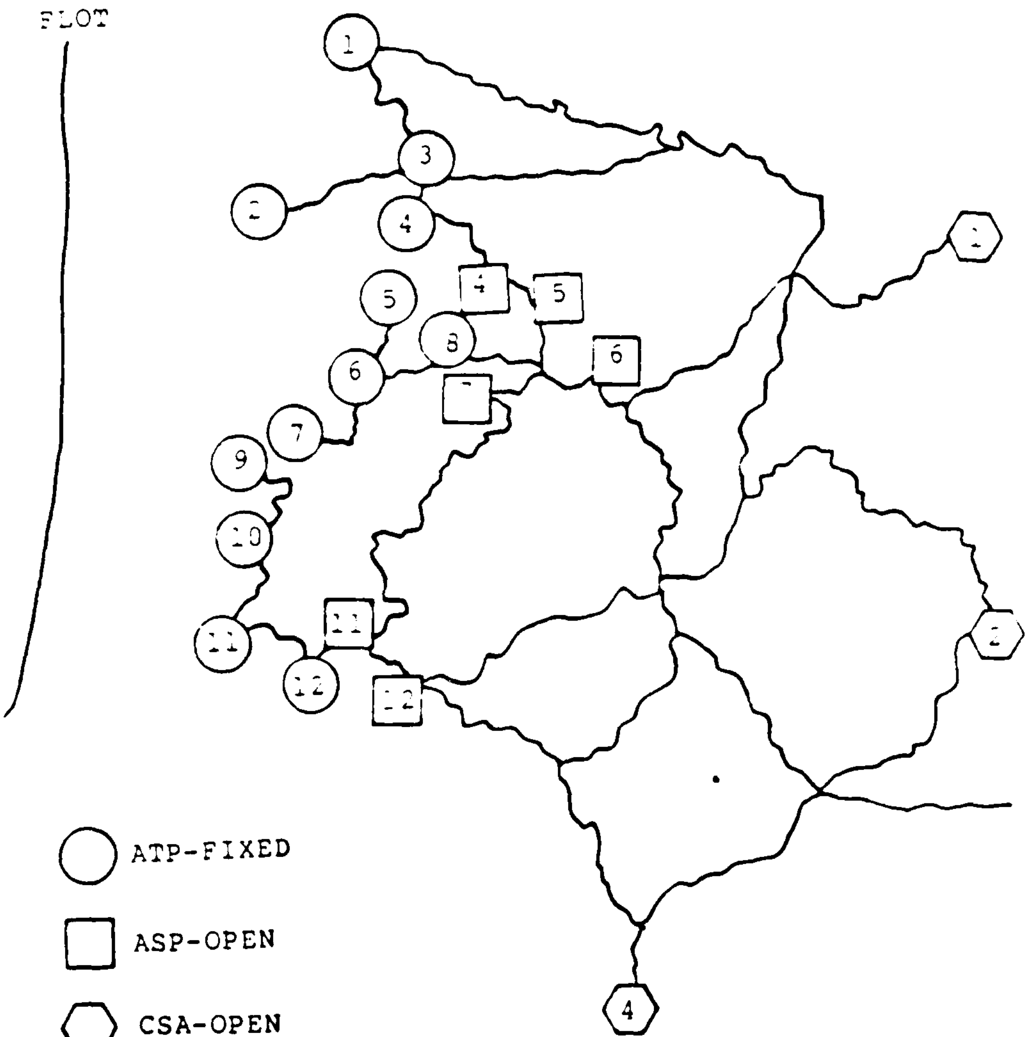

Figure 5. Scenario Solution

execution of the heuristic using the modified constraints to determine optimality and would require subsequent revised guidance by the Corps Commander to the staff.

E. MODELLING THE WADS WITH GAMS

GAMS is an excellent tool for prototype development and solving small to medium sized problems [Ref. 17]. For this thesis, the Corps level was considered without regard to echelons above Corps. For a thorough analysis, optimal location and flow from the Port to the ATPs should be considered. A larger model, in a sequential heuristic form, would have more stages in the sequential solving procedure [Ref. 14 : Ch.18 pp.11-12]. Time period reduction might be required.

A great advantage of GAMS is the ability to effortlessly formulate thousands of equations, view at least a portion of the model generated, and analyze the detailed solution report available. Coupled with on-line error messages, debugging is much easier than other programming languages [Ref. 14 : Ch.18 pp.1-2].

Flexibility for modelling the WADS' myriad of "rules of thumb" is essential. GAMS has the necessary flexibility. No specific model form is presumed or required. GAMS allows the user modelling freedom necessary to analyze the many facets of the WADS.

F. REMARKS

Theoretically, both the MIP and sequential heuristic can model the given scenario and arrive at an optimal solution. Model size, rapid solution times, and "good" solution quality favor the heuristic. A detailed pursuit of the full scale model, including the echelons above Corps, is necessary to conduct a thorough analysis of the WADS. The GAMS formulations presented are prototypes for initial investigations on which to build larger more complete models that include all facets of the WADS.

V. CONCLUSIONS AND RECOMMENDATIONS

The following pages close this thesis with conclusions and recommendations. The questions posed in Chapter II are answered and additional remarks presented. Recommendations for expansion and further research are discussed.

A. CONCLUSIONS

The WADS, at least for Corps level and below, is designed to support the force in the last war but is not adequate for combat under an Airland Battle scenario with the associated increase in ammunition consumption. An increase in lift capacity and a reduction in inventory levels is required to obtain feasible solutions that are either "good" or optimal. Echelons above the Corps level provide little relief to increased consumption rates by the forward brigades when CSA and ASP lift capacities are at a maximum issuing ammunition.

Transportation is feasible at doctrinal levels. However, inventory goals and demand can only be met by close management of transportation assets. Prior to, during, and immediately after high demand periods, transportation constraints are tight. As long as the product of tractor availability and dedicated assets remains above .543 then sufficient transportation assets are on-hand and the WADS is feasible. As transport assets are reduced, more inventory is carried forward with time. When more transportation is made available, less inventory is carried forward.

The sequential heuristic provides a solid approach to solving the problem at hand. With minimum use of CPU time, moderate sized problems can be solved with "good" and possibly optimal solutions. The MIP on the other hand does not appear to have any realistic practical value when using GAMS with ZOOM as a solver. If another model generator and solver were utilized, the MIP might actually be used since the sequential heuristic takes advantage of a GAMS solving technique which may not be available to other software.

Chapter II introduced some natural questions that have arisen as a result of the Airland Battle concept. Each question is discussed in order of presentation from Chapter II:

Question : Will the increased demand for ammunition force changes in the current system? **Answer** : Yes. The models presented indicate a shortage in lift capacities at the CSAs, ASPs, and ATPs. Current inventory goals are not feasible and must be reduced to obtain optimal network flows. Inference for echelons above Corps level is possible. When CSA and ASP lift capacities are entirely devoted to meeting high demand at the ATPs, no new ammunition can be received at the CSA or the ASP from the Port or TSA. This means that echelons above Corps can provide little assistance when lift capacity is not sufficient at lower levels.

Question : Are the heuristics or "rules of thumb" from past wars applicable to future conflicts? **Answer** : No. Heuristics and "rules of thumb" from past wars are based on consumptions rates far lower than simulated consumption rates under the concept of Airland Battle. It can be shown using either model presented, that historical consumption rates with doctrinal parameters and scalars are feasible. Airland Battle consumptions rates are infeasible. The system is currently designed for past conflicts.

Question : What stockage policies can be used to minimize the size of ammunition facilities thereby reducing target signature? **Answer** : Size of ammunition facilities is directly proportional to the amount of ammunition on-hand; common sense. By reducing bypass flows, inventory levels can be more tightly controlled and target signature reduced. Current policy calls for 3-5 days of supply at an ASP. As shown, an inventory goal of 3-5 days of supply is not feasible, while 1-5 days of supply is. The model's tendancy is to carry minimum inventory so by feasibility criteria alone, inventory and target signature is reduced (this is assuming sufficient lift capacity and transportation assets are available). If the efficiency of the system can be improved particularly in the areas of ammunition forecasting and system control, minimal inventory would be required. By increasing lift capacities and allowing for adequate transportation assets to move ammunition forward, inventory levels can be reduced drastically at the ASP. A "rough cut" at specific items to stock can be based on the 20 ammunition types discussed in Chapter II. Straight percentages of inventory levels given by the sequential heuristic will provide an approximate stockage policy by ammunition type to start with.

Question : What is the best placement for ammunition storage facilities? **Answer** : By using a facility location model, optimal or close to optimal solutions for proper placement can be determined from a set of proposed sites. In essence, facility location can be determined with respect to demand, distance between facilities, road conditions, straight line distance to the FLOT, etc. subject to doctrinal "rules."

This concludes the questions from ChapterII. Additional comments follow.

It would appear that MOADS is the proper direction to pursue in concept. Inventory levels are reduced to 1-3 days of supply. This means that target signature for each individual ASP is reduced. By increasing the amount of stockage at the CSA, the same amount of ammunition is fielded in the Corps' area but in a more secure position. Increasing the number of ASPs from 2 to 3 creates additional dispersion which further reduces target signature. A 75% bypass level allows more control over building inventory to meet established goals.

PLS appears to also be a step in the right direction. PLS gives an overall increase in lift capacity network-wide since material handling equipment is not necessarily required to upload or offload vehicles transporting ammunition. This concept could conceivably provide the lift required at the CSA and ASP for feasibility with current doctrinal parameters. Since the ATP no longer exists under this concept, some of the lift assets authorized to the ATPs might be redistributed within the TO.

As mentioned in Chapter IV, transportation assets appear to be marginal. Required amounts of transportation are computed using the ammunition flows as a basis. The numbers are not encouraging for high demand periods. Without sufficient transportation, the WADS will not function. Depending on other than transportation units for assets to make up the difference in required transportation, e.g. dump trucks from engineer units, is poor planning. A realistic, detailed transportation support plan using authorized assets is necessary to properly design the WADS for Airland Battle.

Demand rates still remain a subject of much controversy. Most analysts agree that historical consumption rates are much too low but what is the proper consumption rates for Airland Battle? The quality of Airland Battle consumption rates from simulations or estimation directly affects the design of WADS to support the force. Poor estimates will result in a system that is over designed and one which wastes assets or one which cannot support the units in the field. A distribution for demand would make an inventory theory approach possible and provide a much more powerful examination of what is required to support the forward units. In addition, if a mathematical programming procedure is still desired, there exists a capacitated, stochastic facility location model [Ref. 23 : p. 273].

The models presented are not confined to application with ammunition. The concept of locating facilities and determining flow through those facilities opened is applicable to other logistical areas such as petroleum, water, food, medical, and maintenance operations to mention a few. Of course, the doctrinal constraints would change but the basic ideas would remain the same.

B. RECOMMENDATIONS

Further research in the area of ammunition facility location and ammunition flow is worthwhile. A new model generator and solver designed to take advantage of problem structure could conceivably be undertaken to analyze the WADS theater-wide instead of just Corps level and below. GAMS prototype models are possible for the WADS utilizing the MOADS and PLS concepts for Corps level and below or for a network flow model from the Port to the ATPs without facility location.

Stochastic Inventory theory could also provide a nice approach to analyze the WADS. If a distribution for demand were available this approach is very powerful as it accounts for randomness in ammunition consumption which the deterministic models presented do not.

The dynamic facility location model [Ref. 23 : pp. 269-270] might be undertaken since the forward storage facilities relocate on a regular basis. The dynamic facility location model makes siting decisions as a function of time. This approach has merit particularly for attacking units over long periods of time.

Another idea for WADS analysis might be to ignore doctrinal constraints and model only structural constraints. This concept provides an unbiased analysis of the situation which is free of heuristics and "rules of thumb" from past conflicts. Conceivably, a better way to support the force might be found that would be compatable with available assets. Assuming a close working relationship with the ammunition community, this approach might iteratively arrive at a system that would best support the units in the field.

Finally, a very powerful technique that could be used for either a doctrinal or structural approach is the use of Elastic programming. In an Elastic program, all constraints can be violated at a cost. This is certainly a practical approach and one of great flexability when solving real world problems. As mentioned in Chapter IV, additional assets might be found to loosen the formulation at some cost. Again, an iterative development with the ammunition community would conceivably arrive at a system that could improve field performance.

APPENDIX A. MIXED INTEGER PROGRAM

```
$TITLE MIXED INTEGER PROGRAM

*THESIS MODEL

*CPT MARK J. CAIN                                DATE: 8 MARCH 1987

*MODEL: AN AMMUNITION FACILITY LOCATION AND NETWORK FLOW MODEL FOR
*       A CORPS IN THE THEATER OF OPERATIONS.

SETS I fixed ammunition transfer points /ATP1*ATP12/
     J possible ammunition storage point locations /ASP1*ASP12/
     K possible corps storage point locations /CSA1*CSA4/
     T time periods /T1*T3/

PARAMETER ASPFLOT(J) direct distance from asp j to the flot

          /ASP1  54
           ASP2  59
           ASP3  46
           ASP4  41
           ASP5  45
           ASP6  49
           ASP7  46
           ASP8  42
           ASP9  38
           ASP10 35
           ASP11 33
           ASP12 40/ ;

PARAMETER CSAFLOT(K) direct distance from csa k to the flot

          /CSA1  86
           CSA2  95
           CSA3  97
           CSA4  68/ ;

TABLE DIST(I,J) road distance from atp i to asp j
```

	ASP1	ASP2	ASP3	ASP4	ASP5	ASP6	ASP7	ASP8	ASP9	ASP10	ASP11	ASP12
ATP1	25	32	26	25	30	37	37	42	INF	INF	INF	INF
ATP2	29	23	10	11	16	23	23	28	INF	INF	INF	INF
ATP3	42	36	23	24	29	36	36	41	INF	INF	INF	INF
ATP4	34	28	15	4	9	16	16	21	INF	INF	INF	INF
ATP5	72	66	53	32	27	26	26	31	41	50	58	64
ATP6	65	59	46	25	20	19	19	24	34	43	51	57
ATP7	72	66	53	32	27	26	26	31	41	50	58	64
ATP8	50	44	31	10	5	4	4	9	19	28	36	42
ATP9	INF	INF	INF	INF	66	65	59	54	44	35	27	33
ATP10	INF	INF	INF	INF	58	57	51	46	36	27	19	25
ATP11	INF	INF	INF	INF	51	50	44	39	29	20	12	18
ATP12	INF	INF	INF	INF	41	40	34	29	19	10	2	8 ;

```
TABLE LENGTH(J,K) road distance from asp j to csa k

        CSA1  CSA2  CSA3  CSA4
 ASP1     50    82   112   112
 ASP2     44    76   106   106
 ASP3     57    89   119   119
 ASP4     60    79    81    81
 ASP5     55    74    76    76
 ASP6     48    67    69    69
 ASP7     54    73    75    75
 ASP8     59    78    80    72
 ASP9     69    88    90    62
 ASP10    78    84    86    53
 ASP11    86    76    78    45
 ASP12    84    70    72    39 ;

TABLE HOWFAR(I,K) road distance from atp i to csa k

        CSA1  CSA2  CSA3  CSA4
 ATP1     75   107   106   106
 ATP2     67    99    92    92
 ATP3     80   112   105   105
 ATP4     74    83    85    85
 ATP5     74    93    95    95
 ATP6     67    86    88    88
 ATP7     74    93    95    95
 ATP8     52    71    73    73
 ATP9    117   103   105    72
 ATP10   109    95    97    64
 ATP11   102    88    90    57
 ATP12    92    78    80    47 ;

*PENALTY COSTS ARE CALCULATED USING A LINEAR COMBINATION OF ROAD
*CHARACTERISTICS BASED ON THE FOLLOWING VALUES: TWO LANE-1.00,
*ONE LANE-2.00, AND TRAILS-4.00

TABLE PNCOST1(I,J) penalty cost for road from atp i to asp j

        ASP1 ASP2 ASP3 ASP4 ASP5 ASP6 ASP7 ASP8 ASP9 ASP10 ASP11 ASP12
 ATP1   2.00 2.00 2.00 1.56 1.47 1.38 1.46 1.52 4.00  4.00  4.00  4.00
 ATP2   2.00 2.00 2.00 1.00 1.00 1.00 1.13 1.29 4.00  4.00  4.00  4.00
 ATP3   1.69 1.64 1.43 1.00 1.45 1.36 1.44 1.51 4.00  4.00  4.00  4.00
 ATP4   1.80 1.77 1.59 1.00 1.00 1.00 1.19 1.38 4.00  4.00  4.00  4.00
 ATP5   1.92 1.91 1.89 2.16 2.37 2.42 2.54 2.45 2.34  2.28  2.24  2.13
 ATP6   1.69 1.66 1.56 1.64 1.80 1.75 2.00 2.00 2.00  2.00  2.00  1.89
 ATP7   1.72 1.70 1.62 1.72 1.85 1.88 2.00 2.00 2.00  2.00  2.00  1.91
 ATP8   1.60 1.55 1.36 2.00 1.20 1.00 2.00 2.00 2.00  2.00  2.00  1.86
 ATP9   4.00 4.00 4.00 4.00 1.76 1.77 1.80 1.78 1.73  1.66  1.56  1.45
 ATP10  4.00 4.00 4.00 4.00 1.72 1.74 1.76 1.74 1.67  1.56  1.37  1.28
 ATP11  4.00 4.00 4.00 4.00 1.69 1.70 1.73 1.69 1.59  1.40  1.00  1.00
 ATP12  4.00 4.00 4.00 4.00 1.85 1.88 1.94 1.93 1.89  1.80  1.00  1.00 ;

TABLE PNCOST2(J,K) penalty cost for road from asp j to csa k

        CSA1 CSA2 CSA3 CSA4
```

```
 ASP1  1.82 1.61 2.07 2.07
 ASP2  1.80 1.58 2.08 2.08
 ASP3  1.84 1.64 2.07 2.07
 ASP4  1.70 1.35 2.21 2.21
 ASP5  1.76 1.38 2.29 2.29
 ASP6  1.88 1.42 2.42 2.42
 ASP7  1.83 1.42 2.35 2.35
 ASP8  1.85 1.46 2.33 2.29
 ASP9  1.87 1.52 2.29 2.34
 ASP10 1.88 2.43 3.21 2.40
 ASP11 1.90 2.47 3.33 2.47
 ASP12 2.22 2.60 3.53 2.69 ;

TABLE PNCOST3(I,K) penalty cost for road from atp i to csa k

       CSA1 CSA2 CSA3 CSA4
 ATP1  1.88 1.70 2.06 2.06
 ATP2  1.87 1.68 2.07 2.07
 ATP3  1.73 1.60 1.93 1.93
 ATP4  1.78 1.34 2.15 2.15
 ATP5  1.76 1.70 2.42 2.42
 ATP6  1.52 1.51 2.30 2.30
 ATP7  1.57 1.55 2.27 2.27
 ATP8  1.38 1.41 2.36 2.36
 ATP9  2.01 2.23 2.88 2.13
 ATP10 2.01 2.25 2.94 2.14
 ATP11 2.01 2.27 3.02 2.16
 ATP12 2.12 2.44 3.28 2.40 ;

TABLE DMNATP(I,T) demand at atp i in time period t
         T1    T2    T3
 ATP1  .124  .124  .643
 ATP2  .115  .115  .574
 ATP3  .115  .115  .575
 ATP4  .111  .111  .621
 ATP5  .124  .124  .651
 ATP6  .124  .124  .651
 ATP7  .109  .109  .500
 ATP8  .487  .487 2.001
 ATP9  .354  .354 1.483
 ATP10 .144  .144  .744
 ATP11 .258  .258 1.215
 ATP12 .490  .490 2.258 ;

SCALARS NUMDIV  number of divisions assigned to the corps /3/
        NUMASP  number of asps assigned to the corps /6/
        NUMCSA  number of csas assigned to the corps /3/
        CORRES  number of atps directly serviced by one asp /2/
        RLTN    number of atps indirectly serviced by one csa /2/
        CONFIG  number of atps directly serviced by one csa /4/
        PORASP  percentage of demand supplied to atp by asp /.2/
        PORCSA  percentage of demand supplied to asp by csa /.2/
        PERCSA  percentage of demand supplied to atp by csa /.8/
        TOFAR   maximum distance from atp to asp /30/
        FARENF  maximum distance from asp to csa /100/
        DAMNFAR maximum distance from atp to csa /130/
```

```
        TUNE    adjustable scalar to tune the objective function /.01/
        SCALE   put asp and csa in terms of atp distance /20/
        ADJUST  user adjustable scalar to shape curve /1.00/
        MAXCSA  maximum lift capacity of the csa /10.664/
        MAXASP  maximum lift capacity of the asp /2.732/
        TRIPS   possible round trips per day from csa k to atp i /3/
        ROUND   possible round trips per day from csa k to asp j /4/
        TRUCKS  number of tractor trailers authorized per Corps /300/
        AVGHAUL average haul weight per trailer /.015/
        AVAIL   tractor availability on any given day /.80/
        AMMO    percentage of total tractor trailers hauling ammo /.80/
        LEVEL   work level devote to issue at csa k /.333/
        MAXINV  maximum inventory of the asp in days of supply /5/
        MININV  minimum inventory of the asp in days of supply /1/ ;

*THE FOLLOWING IS A PENALTY COST BASED ON A USER ADJUSTABLE CONVEX
*FUNCTION. THE CLOSER AN AMMUNITION FACILITY IS TO THE FLOT, THE
*HIGHER PENALTY COST PAID.............

PARAMETER PROX(J) danger curve for asp j ;
          PROX(J)=(SCALE/ASPFLOT(J))**ADJUST ;

PARAMETER CLOSE(K) danger curve for csa k ;
          CLOSE(K)=(SCALE/CSAFLOT(K))**ADJUST ;

DISPLAY PROX, CLOSE ;

*THE FOLLOWING 0-1 PARAMETERS ARE USED FOR "SUCH THAT" OPERATORS TO
*SCREEN OUT DISTANCES NOT IN ACCORDANCE WITH ARMY DOCTRINE.........

PARAMETER MAXDIST(I,J) filter for dist ij matrix ;
          MAXDIST(I,J) $ (DIST(I,J) LE TOFAR)=1 ;

PARAMETER MAXLENG(J,K) filter for length jk matrix ;
          MAXLENG(J,K) $ (LENGTH(J,K) LE FARENF)=1 ;

PARAMETER MAXFAR(I,K) filter for howfar ik matrix ;
          MAXFAR(I,K) $ (HOWFAR(I,K) LE DAMNFAR)=1 ;

DISPLAY MAXDIST,MAXLENG,MAXFAR ;

*THE FOLLOWING ARE TEN ERROR CHECKS FOR FURTHER SCREENING
*OF DATA AND MODEL FORMULATION.

*THIS INSURES THAT 4 ATP LOCATIONS HAVE BEEN INPUT FOR EACH DIVISION.

PARAMETER CHECK1(I) error check for atp index;
          CHECK1(I) $ (CARD(I)/4 NE NUMDIV)=1;
PARAMETER ERRORCNT1 error check one;
          ERRORCNT1 $ (SUM(I,CHECK1(I)) NE 0)=1;
ABORT $(ERRORCNT1) "EXECUTION TERMINATED DUE TO ATP INDEX ERROR";

*THIS INSURES THAT THERE IS AT LEAST ONE PROPOSED ASP LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ATP.

PARAMETER CHECK2(I) error check for atp asp distance feasibility;
```

```
        CHECK2(I) $ (SUM(J,MAXDIST(I,J)) EQ 0)=1;
PARAMETER ERRORCNT2 error check two;
        ERRORCNT2 $ (SUM(I,CHECK2(I)) NE 0)=1;
ABORT $(ERRORCNT2) "EXECUTION TERMINATED NO ASP WITHIN TOFAR OF ATP";

*THIS INSURES THAT THERE IS AT LEAST ONE PROPOSED CSA LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ATP.

PARAMETER CHECK3(I) error check for atp csa distance feasibility;
        CHECK3(I) $ (SUM(K,MAXFAR(I,K)) EQ 0)=1;
PARAMETER ERRORCNT3 error check three;
        ERRORCNT3 $ (SUM(I,CHECK3(I)) NE 0)=1;
ABORT $(ERRORCNT3) "EXECUTION TERMINATED NO CSA WITHIN DAMNFAR OF ATP";

*THIS INSURED THAT THERE IS AT LEAST ONE PROPOSED CSA LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ASP.

PARAMETER CHECK4(J) error check for asp csa distance feasiblilty;
        CHECK4(J) $ (SUM(K,MAXLENG(J,K)) EQ 0)=1;
PARAMETER ERRORCNT4 error check three a ;
        ERRORCNT4 $ (SUM(J,CHECK4(J)) NE 0)=1;
ABORT $(ERRORCNT4) "EXECUTION TERMINATED NO CSA WITHIN FARENF OF ASP";

*ASP MUST NOT BE PLACED TOO CLOSE TO THE FLOT.

PARAMETER CHECK4A(J) error check for asp flot straight line distance ;
        CHECK4A(J) $ (ASPFLOT(J) LE 20)=1 ;
PARAMETER ERRORCNT4A error check four a ;
        ERRORCNT4A $ (SUM(J, CHECK4A(J)) NE 0)=1 ;
ABORT $(ERRORCNT4A) "EXECUTION TERMINATED ASP TO CLOSE TO FLOT" ;

*CSA MUST NOT BE PLACED TOO CLOSE TO THE FLOT.

PARAMETER CHECK4B(K) error check for csa flot straight line distance ;
        CHECK4B(K) $ (CSAFLOT(K) LE 50)=1 ;
PARAMETER ERRORCNT4B error check four b ;
        ERRORCNT4B $ (SUM(K, CHECK4B(K)) NE 0)=1 ;
ABORT $(ERRORCNT4B) "EXECUTION TERMINATED CSA TO CLOSE TO FLOT" ;

*AS DEFINED IN THE PROGRAM, PENALTY COSTS WILL VARY BETWEEN 1.00 AND
*4.00. THE FOLLOWING WILL INSURE CORRECT COMPUTATION.

PARAMETER CHECK5(I,J) error check for penalty cost calculations;
 CHECK5(I,J) $ (PNCOST1(I,J) GT 4.0 OR PNCOST1(I,J) LT 1.0)=1;
PARAMETER ERRORCNT5 error check five;
        ERRORCNT5 $ (SUM((I,J),CHECK5(I,J)) NE 0)=1;
ABORT $(ERRORCNT5) "EXECUTION TERMINATED PENALTY COST MISCALCULATION";

PARAMETER CHECK5A(J,K) error check for penalty cost calculations;
 CHECK5A(J,K) $ (PNCOST2(J,K) GT 4.0 OR PNCOST2(J,K) LT 1.0)=1;
PARAMETER ERRORCNT5A error check five a;
        ERRORCNT5A $ (SUM((J,K),CHECK5A(J,K)) NE 0)=1;
ABORT $(ERRORCNT5A) "EXECUTION TERMINATED PENALTY COST MISCALCULATION";

PARAMETER CHECK6(I,K) error check for penalty cost calculations;
```

```
 CHECK6(I,K) $ (PNCOST3(I,K) GT 4.0 OR PNCOST3(I,K) LT 1.0)=1;
PARAMETER ERRORCNT6 error check six;
          ERRORCNT6 $ (SUM((I,K),CHECK6(I,K)) NE 0)=1;
ABORT $(ERRORCNT6) "EXECUTION TERMINATED PENALTY COST MISCALCULATION" ;

*THIS ERROR CHECK WILL INSURE THAT THE DEMAND DATA IS IN QUANTITIES
*THAT THE ATP CAN REASONABLE HANDLE.

PARAMETER CHECK7(I,T) error check for demand at atp i ;
          CHECK7(I,T) $ (DMNATP(I,T) GT 2.500)=1 ;
PARAMETER ERRORCNT7 error check seven ;
          ERRORCNT7 $ (SUM((I,T), CHECK7(I,T)) NE 0)=1 ;
ABORT $(ERRORCNT7) "EXECUTION TERMINATED DEMAND EXCEED ATP CAPACITY" ;

*THE FOLLOWING FIVE PARAMETERS ARE USER ADJUSTABLE TACTICAL COSTS
*FOR MOVING AND HOLDING AMMUNITION.................

PARAMETER SHIP1(J,K,T) shipping cost from csa k to asp j in period t ;
          SHIP1(J,K,T)=1.00 ;

PARAMETER SHIP2(I,J,T) shipping cost from asp j to atp i in period t ;
          SHIP2(I,J,T)=1.00 ;

PARAMETER SHIP3(I,K,T) shipping cost from csa k to atp i in period t ;
          SHIP3(I,K,T)=1.00 ;

PARAMETER INV1(J,T) inventory cost at asp j in period t ;
          INV1(J,T)=1.00 ;

VARIABLES X(I,J)    asp j services atp i (1=yes and 0=no)
          A(J,K)    csa k services asp j (1=yes and 0=no)
          Z(I,K)    csa k services atp i (1=yes and 0=no)
          Y(J)      asp located at site j (1=yes and 0=no)
          B(K)      csa located at site k (1=yes and 0=no)
          F(J,K,T)   flow from csa k to asp j in period t
          TH(I,K,T) flow from csa k to atp i in period t
          EF(I,J,T) flow from asp j to atp i in period t
          IASP(J,T) inventory at asp j at the end of time period t
          COST      objective variable ;

BINARY VARIABLES X,A,Z,Y,B ;

POSITIVE VARIABLES F, TH, EF, IASP ;

EQUATIONS
 ONESITE(I)       assign atp to one asp
 SERVICE(J)       asp services two atps
 BOUND1(I,J,T)    upper bound for ef ij
 VARUPBD1(I,J)    variable upper bound for x ij

 HANNA(J)         assign asp to one csa
 SUPPORT(K)       csa services two asps
 BOUND2(J,K,T)    upper bound for f jk
 VARUPBD2(J,K)    variable upper bound for a jk

 SINGLE(I)        assign atp to one csa
```

```
HELP(K)           csa services four atps
BOUND3(I,K,T)     upper bound for th ik
VARUPBD3(I,K)     variable upper bound for z ik

LIMIT             number of asps are limited by numasp
CEILING           number of csas are limited by numcsa

BALASP(J,T)       flow into asp j must equal flow out
BALATP(I,T)       flow into atp i must equal flow out
CAPCSA(K,T)       lift capacity of csa
CAPASP(J,T)       lift capacity of asp
STABLE(K)         surrogate long run flow balance for csa k
UPPER(J,T)        maximum inventory at asp
LOWER(J,T)        minimum inventory at asp
TRANS(T)          trans assets available to haul ammo in time period t
LONGRUN           throughput long run contribution to demand

OBJFCN            definition of cost ;


ONESITE(I)..      SUM(J $ (MAXDIST(I,J)), X(I,J))=E=1 ;

SERVICE(J)..      SUM(I $ (MAXDIST(I,J)), X(I,J))=E=CORRES*Y(J) ;

BOUND1(I,J,T)..   EF(I,J,T)=L=MAXASP*X(I,J) ;

VARUPBD1(I,J) $ MAXDIST(I,J)..  X(I,J)=L=Y(J) ;

HANNA(J)..        SUM(K $ (MAXLENG(J,K)), A(J,K))=E=Y(J) ;

SUPPORT(K)..      SUM(J $ (MAXLENG(J,K)), A(J,K))=E=RLTN*B(K) ;

BOUND2(J,K,T)..   F(J,K,T)=L=MAXASP*A(J,K) ;

VARUPBD2(J,K) $ MAXLENG(J,K)..  A(J,K)=L=B(K) ;

SINGLE(I)..       SUM(K $ MAXFAR(I,K), Z(I,K))=E=1 ;

HELP(K)..         SUM(I $ MAXFAR(I,K), Z(I,K))=E=CONFIG*B(K) ;

BOUND3(I,K,T)..   TH(I,K,T)=L=MAXCSA*Z(I,K) ;

VARUPBD3(I,K) $ MAXFAR(I,K)..  Z(I,K)=L=B(K) ;

LIMIT..           SUM(J,Y(J))=E=NUMASP ;

CEILING..         SUM(K,B(K))=E=NUMCSA ;

BALASP(J,T)..   -SUM(K $ MAXLENG(J,K), F(J,K,T))+SUM(I $ MAXDIST(I,J),
                EF(I,J,T))-IASP(J,T-1)+IASP(J,T)=E=0 ;

BALATP(I,T)..   -SUM(J $ MAXDIST(I,J), EF(I,J,T))-SUM(K $ MAXFAR(I,K),
                TH(I,K,T))=E=-DMNATP(I,T) ;

CAPCSA(K,T)..   SUM(J $ MAXLENG(J,K), F(J,K,T))+SUM(I $ MAXFAR(I,K),
                TH(I,K,T))=L=MAXCSA*B(K) ;
```

```
 CAPASP(J,T)..  SUM(K $ MAXLENG(J,K), F(J,K,T))+SUM(I $ MAXDIST(I,J),
                EF(I,J,T))=L=MAXASP*Y(J) ;

 STABLE(K)..    SUM((I,T) $ MAXFAR(I,K), TH(I,K,T))+
                SUM((J,T) $ MAXLENG(J,K), F(J,K,T))=L=LEVEL*
                CARD(T)*MAXCSA*B(K) ;

 UPPER(J,T) $ (ORD(T) LT CARD(T))..  IASP(J,T)=L=MAXINV*
                                     SUM(I,DMNATP(I,T+1)*X(I,J)) ;

 LOWER(J,T) $ (ORD(T) LT CARD(T))..  IASP(J,T)=G=MININV*
                                     SUM(I,DMNATP(I,T+1)*X(I,J)) ;

 TRANS(T)..     (SUM((I,K) $MAXFAR(I,K), TH(I,K,T))/TRIPS)+
                (SUM((J,K) $MAXLENG(J,K), F(J,K,T   ROUND)=L=
                TRUCKS*AVGHAUL*AVAIL*AMMO ;

 LONGRUN..      SUM((I,K,T) $ MAXFAR(I,K), TH(I,K,T))=E=PERCSA*
                SUM((I,T), DMNATP(I,T)) ;

 OBJFCN..         COST=E=
  SUM((J,K,T) $ MAXLENG(J,K), SHIP1(J,K,T)*F(J,K,T))+
  SUM((I,J,T) $ MAXDIST(I,J), SHIP2(I,J,T)*EF(I,J,T))+
  SUM((I,K,T) $ MAXFAR(I,K),  SHIP3(I,K,T)*TH(I,K,T))+
  SUM((J,T), INV1(J,T)*IASP(J,T))+
  SUM(K, CLOSE(K)*B(K))+SUM(J, PROX(J)*Y(J))+
  SUM((I,J) $ MAXDIST(I,J), TUNE*DIST(I,J)*PNCOST1(I,J)*X(I,J))+
  SUM((J,K) $ MAXLENG(J,K), TUNE*LENGTH(J,K)*PNCOST2(J,K)*A(J,K))+
  SUM((I,K) $ MAXFAR(I,K),  TUNE*HOWFAR(I,K)*PNCOST3(I,K)*Z(I,K)) ;

MODEL LOCATION /ALL/ ;

OPTION LIMROW=12, LIMCOL=0, ITERLIM=10000, OPTCR=.10, RESLIM=600.00 ;

SOLVE LOCATION USING MIP MINIMIZING COST ;

DISPLAY X.L, A.L, Z.L, Y.L, B.L ;

DISPLAY F.L, IASP.L, TH.L, EF.L ;

*THE FOLLOWING ARE POST-OPTIMALITY CALCULATIONS TO DETERMINE THE NUMBER
*OF TRACTOR TRAILERS REQUIRED TO SUPPORT THE NETWORK..................

PARAMETER TRANSF(J,K,T) tractor trailers needed on jk arc ;
          TRANSF(J,K,T)=F.L(J,K,T)/AVGHAUL ;

PARAMETER TRANSEF(I,J,T) tractor trailers needed on ij arc ;
          TRANSEF(I,J,T)=EF.L(I,J,T)/AVGHAUL ;

PARAMETER TRANSTH(I,K,T) tractor trailers needed on ik arc ;
          TRANSTH(I,K,T)=TH.L(I,K,T)/AVGHAUL ;

PARAMETER STRANSF(T) total tractor trailers needed in time period t ;
          STRANSF(T)=SUM((J,K), TRANSF(J,K,T)) ;
```

```
PARAMETER STRANSEF(T) total tractor trailers needed in time period t ;
          STRANSEF(T)=SUM((I,J), TRANSEF(I,J,T)) ;

PARAMETER STRANSTH(T) total tractor trailers needed in time period t ;
          STRANSTH(T)=SUM((I,K), TRANSTH(I,K,T)) ;

PARAMETER TIMETOT(T) total corps requirement for time period t ;
          TIMETOT(T)=STRANSF(T)+STRANSEF(T)+STRANSTH(T) ;

DISPLAY TRANSF, STRANSF, TRANSEF, STRANSEF, TRANSTH,
        STRANSTH, TIMETOT ;
```

APPENDIX B. SEQUENTIAL HEURISTIC

```
$TITLE A SEQUENTIAL HEURISTIC

*THESIS MODEL

*CPT MARK J. CAIN                              DATE: 8 MARCH 1987

*MODEL: AN AMMUNITION FACILITY LOCATION AND NETWORK FLOW MODEL FOR
*       A CORPS IN THE THEATER OF OPERATIONS.

$ONTEXT
This sequential heuristic models a Corps level "slice" of the U.S. Army
Wartime Ammunition Distribution System (WADS). The heuristic is composed
of a binary integer program for the first module and a network flow model
for the second module. Maximum use of the "such that" operator ($) is
used to generate only those variables and constraints necessary to
properly model the system. Solution times and size of the problem that
can be solved favor this approach. A mixed integer program is the proper
procedure but solution times in excess of 600 CPU seconds limited practi-
cal value for analysis.
$OFFTEXT

SETS I fixed ammunition transfer points /ATP1*ATP12/
     J possible ammunition storage point locations /ASP1*ASP12/
     K possible corps storage point locations /CSA1*CSA4/
     T time periods              /T1*T30/ ;

PARAMETER ASPFLOT(J) direct distance from asp j to the flot

          /ASP1  54
           ASP2  59
           ASP3  46
           ASP4  41
           ASP5  45
           ASP6  49
           ASP7  46
           ASP8  42
           ASP9  38
           ASP10 35
           ASP11 33
           ASP12 40/ ;

PARAMETER CSAFLOT(K) direct distance from csa k to the flot

          /CSA1  86
           CSA2  95
           CSA3  97
           CSA4  68/ ;

TABLE DIST(I,J) road distance from atp i to asp j

       ASP1 ASP2 ASP3 ASP4 ASP5 ASP6 ASP7 ASP8 ASP9 ASP10 ASP11 ASP12
```

ATP1	25	32	26	25	30	37	37	42	INF	INF	INF	INF
ATP2	29	23	10	11	16	23	23	28	INF	INF	INF	INF
ATP3	42	36	23	24	29	36	36	41	INF	INF	INF	INF
ATP4	34	28	15	4	9	16	16	21	INF	INF	INF	INF
ATP5	72	66	53	32	27	26	26	31	41	50	58	64
ATP6	65	59	46	25	20	19	19	24	34	43	51	57
ATP7	72	66	53	32	27	26	26	31	41	50	58	64
ATP8	50	44	31	10	5	4	4	9	19	28	36	42
ATP9	INF	INF	INF	INF	66	65	59	54	44	35	27	33
ATP10	INF	INF	INF	INF	58	57	51	46	36	27	19	25
ATP11	INF	INF	INF	INF	51	50	44	39	29	20	12	18
ATP12	INF	INF	INF	INF	41	40	34	29	19	10	2	8 ;

TABLE LENGTH(J,K) road distance from asp j to csa k

	CSA1	CSA2	CSA3	CSA4
ASP1	50	82	112	112
ASP2	44	76	106	106
ASP3	57	89	119	119
ASP4	60	79	81	81
ASP5	55	74	76	76
ASP6	48	67	69	69
ASP7	54	73	75	75
ASP8	59	78	80	72
ASP9	69	88	90	62
ASP10	78	84	86	53
ASP11	86	76	78	45
ASP12	84	70	72	39 ;

TABLE HOWFAR(I,K) road distance from atp i to csa k

	CSA1	CSA2	CSA3	CSA4
ATP1	75	107	106	106
ATP2	67	99	92	92
ATP3	80	112	105	105
ATP4	74	83	85	85
ATP5	74	93	95	95
ATP6	67	86	88	88
ATP7	74	93	95	95
ATP8	52	71	73	73
ATP9	117	103	105	72
ATP10	109	95	97	64
ATP11	102	88	90	57
ATP12	92	78	80	47 ;

*PENALTY COSTS ARE CALCULATED USING A LINEAR COMBINATION OF ROAD
*CHARACTERISTICS BASED ON THE FOLLOWING VALUES: TWO LANE-1.00,
*ONE LANE-2.00, AND TRAILS-4.00

TABLE PNCOST1(I,J) penalty cost for road from atp i to asp j

	ASP1	ASP2	ASP3	ASP4	ASP5	ASP6	ASP7	ASP8	ASP9	ASP10	ASP11	ASP12
ATP1	2.00	2.00	2.00	1.56	1.47	1.38	1.46	1.52	4.00	4.00	4.00	4.00
ATP2	2.00	2.00	2.00	1.00	1.00	1.00	1.13	1.29	4.00	4.00	4.00	4.00
ATP3	1.69	1.64	1.43	1.00	1.45	1.36	1.44	1.51	4.00	4.00	4.00	4.00
ATP4	1.80	1.77	1.59	1.00	1.00	1.00	1.19	1.38	4.00	4.00	4.00	4.00

```
ATP5   1.92 1.91 1.89 2.16 2.37 2.42 2.54 2.45 2.34  2.28  2.24  2.13
ATP6   1.69 1.66 1.56 1.64 1.80 1.75 2.00 2.00 2.00  2.00  2.00  1.89
ATP7   1.72 1.70 1.62 1.72 1.85 1.88 2.00 2.00 2.00  2.00  2.00  1.91
ATP8   1.60 1.55 1.36 2.00 1.20 1.00 2.00 2.00 2.00  2.00  2.00  1.86
ATP9   4.00 4.00 4.00 4.00 1.76 1.77 1.80 1.78 1.73  1.66  1.56  1.45
ATP10  4.00 4.00 4.00 4.00 1.72 1.74 1.76 1.74 1.67  1.56  1.37  1.28
ATP11  4.00 4.00 4.00 4.00 1.69 1.70 1.73 1.69 1.59  1.40  1.00  1.00
ATP12  4.00 4.00 4.00 4.00 1.85 1.88 1.94 1.93 1.89  1.80  1.00  1.00 ;

TABLE PNCOST2(J,K) penalty cost for road from asp j to csa k

        CSA1 CSA2 CSA3 CSA4
 ASP1   1.82 1.61 2.07 2.07
 ASP2   1.80 1.58 2.08 2.08
 ASP3   1.84 1.64 2.07 2.07
 ASP4   1.70 1.35 2.21 2.21
 ASP5   1.76 1.38 2.29 2.29
 ASP6   1.88 1.42 2.42 2.42
 ASP7   1.83 1.42 2.35 2.35
 ASP8   1.85 1.46 2.33 2.29
 ASP9   1.87 1.52 2.29 2.34
 ASP10  1.88 2.43 3.21 2.40
 ASP11  1.90 2.47 3.33 2.47
 ASP12  2.22 2.60 3.53 2.69 ;

TABLE PNCOST3(I,K) penalty cost for road from atp i to csa k

        CSA1 CSA2 CSA3 CSA4
 ATP1   1.88 1.70 2.06 2.06
 ATP2   1.87 1.68 2.07 2.07
 ATP3   1.73 1.60 1.93 1.93
 ATP4   1.78 1.34 2.15 2.15
 ATP5   1.76 1.70 2.42 2.42
 ATP6   1.52 1.51 2.30 2.30
 ATP7   1.57 1.55 2.27 2.27
 ATP8   1.38 1.41 2.36 2.36
 ATP9   2.01 2.23 2.88 2.13
 ATP10  2.01 2.25 2.94 2.14
 ATP11  2.01 2.27 3.02 2.16
 ATP12  2.12 2.44 3.28 2.40 ;

TABLE DMNATP(I,T) demand at atp i in time period t
          T1    T2    T3    T4    T5    T6    T7    T8     T9   T10   T11
 ATP1   .124  .124  .643  .564  .197  .197  .197  .197   .643  .126  .126
 ATP2   .115  .115  .574  .503  .176  .176  .176  .176   .574  .118  .118
 ATP3   .115  .115  .575  .503  .176  .176  .176  .176   .575  .118  .118
 ATP4   .111  .111  .621  .551  .193  .193  .193  .193   .621  .113  .113
 ATP5   .124  .124  .651  .570  .200  .200  .200  .200   .651  .127  .127
 ATP6   .124  .124  .651  .570  .199  .199  .199  .199   .651  .127  .127
 ATP7   .109  .109  .500  .457  .160  .160  .160  .160   .500  .111  .111
 ATP8   .487  .487 2.001 1.936  .678  .678  .678  .678  2.001  .498  .498
 ATP9   .354  .354 1.483 1.395  .488  .488  .488  .488  1.483  .354  .354
 ATP10  .144  .144  .744  .648  .227  .227  .227  .227   .744  .144  .144
 ATP11  .258  .258 1.215 1.085  .380  .380  .380  .380  1.215  .258  .258
 ATP12  .490  .490 2.258 2.088  .731  .731  .731  .731  2.258  .490  .490
```

```
+        T12  T13  T14  T15   T16   T17   T18   T19    T20    T21    T22
ATP1   .126 .128 .128 .128  .128  .128  .128  .128   .501   .428   .428
ATP2   .118 .119 .119 .119  .119  .119  .119  .119   .445   .380   .380
ATP3   .118 .119 .119 .119  .119  .119  .119  .119   .445   .380   .380
ATP4   .113 .114 .114 .114  .114  .114  .114  .114   .489   .430   .430
ATP5   .127 .129 .129 .129  .129  .129  .129  .129   .508   .433   .433
ATP6   .127 .129 .129 .129  .129  .129  .129  .129   .508   .433   .433
ATP7   .111 .112 .112 .112  .112  .112  .112  .112   .382   .345   .345
ATP8   .498 .504 .504 .504  .504  .504  .540  .504  1.489  1.482  1.482
ATP9   .354 .354 .354 .354  .354  .354  .354  .354  1.106  1.040  1.040
ATP10  .144 .144 .144 .144  .144  .144  .144  .114   .574   .486   .486
ATP11  .285 .258 .258 .258  .258  .258  .258  .258   .926   .810   .810
ATP12  .490 .490 .490 .490  .490  .490  .490  .490  1.698  1.616  1.616

+         T23    T24   T25    T26   T27   T28   T29   T30
ATP1     .414   .414  .124   .124  .124  .124  .124  .124
ATP2     .367   .367  .115   .115  .115  .115  .115  .115
ATP3     .367   .367  .115   .115  .115  .115  .115  .115
ATP4     .416   .416  .111   .111  .111  .111  .111  .111
ATP5     .419   .419  .124   .124  .124  .124  .124  .124
ATP6     .418   .418  .124   .124  .124  .124  .124  .124
ATP7     .334   .334  .109   .109  .109  .109  .109  .109
ATP8    1.432  1.432  .487   .487  .487  .487  .487  .487
ATP9    1.040  1.040  .354   .354  .354  .354  .354  .354
ATP10    .486   .486  .144   .144  .144  .144  .144  .144
ATP11    .810   .810  .258   .258  .258  .258  .258  .258
ATP12   1.616  1.616  .490   .490  .490  .490  .490  .490 ;

SCALARS NUMDIV   number of divisions per corps /3/
        NUMASP   number of asps assigned to the corps /6/
        NUMCSA   number of csas assigned to the corps /3/
        CORRES   number of atps directly serviced by one asp /2/
        RLTN     number of atps indirectly serviced by one csa /4/
        CONFIG   number of atps directly serviced by one csa /4/
        PORASP   percentage of demand supplied to atp by asp /.2/
        PORCSA   percentage of demand supplied to asp by csa /.2/
        PERCSA   percentage of demand supplied to atp by csa /.8/
        TOFAR    maximum distance from atp to asp /30/
        FARENF   maximum distance from asp to csa /100/
        DAMNFAR  maximum distance from atp to csa /130/
        TUNE     adjustable scalar to tune the objective function /.01/
        SCALE    put asp and csa in terms of atp distance /20/
        ADJUST   user adjustable scalar to shape curve /1.00/ ;

*THE FOLLOWING IS A PENALTY COST BASED ON A USER ADJUSTABLE CONVEX
*FUNCTION. THE CLOSER AN AMMUNITION FACILITY IS TO THE FLOT, THE
*HIGHER PENALTY COST PAID.............

PARAMETER PROX(J) danger curve for asp j ;
          PROX(J)=(SCALE/ASPFLOT(J))**ADJUST ;

PARAMETER CLOSE(K) danger curve for csa k ;
          CLOSE(K)=(SCALE/CSAFLOT(K))**ADJUST ;

DISPLAY PROX, CLOSE ;
```

```
*THE FOLLOWING 0-1 PARAMETERS ARE USED FOR "SUCH THAT" OPERATORS TO
*SCREEN OUT DISTANCES NOT IN ACCORDANCE WITH ARMY DOCTRINE.........

PARAMETER MAXDIST(I,J) filter for dist ij matrix ;
          MAXDIST(I,J) $ (DIST(I,J) LE TOFAR)=1 ;

PARAMETER MAXLENG(J,K) filter for length jk matrix ;
          MAXLENG(J,K) $ (LENGTH(J,K) LE FARENF)=1 ;

PARAMETER MAXFAR(I,K) filter for howfar ik matrix ;
          MAXFAR(I,K) $ (HOWFAR(I,K) LE DAMNFAR)=1 ;

DISPLAY MAXDIST,MAXLENG,MAXFAR ;

*THE FOLLOWING ARE TEN ERROR CHECKS FOR FURTHER SCREENING
*OF DATA AND MODEL FORMULATION.

*THIS INSURES THAT 4 ATP LOCATIONS HAVE BEEN INPUT FOR EACH DIVISION.

PARAMETER CHECK1(I) error check for atp index;
          CHECK1(I) $ (CARD(I)/4 NE NUMDIV)=1;
PARAMETER ERRORCNT1 error check one;
          ERRORCNT1 $ (SUM(I,CHECK1(I)) NE 0)=1;
ABORT $(ERRORCNT1) "EXECUTION TERMINATED DUE TO ATP INDEX ERROR";

*THIS INSURES THAT THERE IS AT LEAST ONE PROPOSED ASP LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ATP.

PARAMETER CHECK2(I) error check for atp asp distance feasibility;
          CHECK2(I) $ (SUM(J,MAXDIST(I,J)) EQ 0)=1;
PARAMETER ERRORCNT2 error check two;
          ERRORCNT2 $ (SUM(I,CHECK2(I)) NE 0)=1;
ABORT $(ERRORCNT2) "EXECUTION TERMINATED NO ASP WITHIN TOFAR OF ATP";

*THIS INSURES THAT THERE IS AT LEAST ONE PROPOSED CSA LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ATP.

PARAMETER CHECK3(I) error check for atp csa distance feasibility;
          CHECK3(I) $ (SUM(K,MAXFAR(I,K)) EQ 0)=1;
PARAMETER ERRORCNT3 error check three;
          ERRORCNT3 $ (SUM(I,CHECK3(I)) NE 0)=1;
ABORT $(ERRORCNT3) "EXECUTION TERMINATED NO CSA WITHIN DAMNFAR OF ATP";

*THIS INSURED THAT THERE IS AT LEAST ONE PROPOSED CSA LOCATION WITHIN THE
*FEASIBLE DISTANCE TO AN ASP.

PARAMETER CHECK4(J) error check for asp csa distance feasiblilty;
          CHECK4(J) $ (SUM(K,MAXLENG(J,K)) EQ 0)=1;
PARAMETER ERRORCNT4 error check three a ;
          ERRORCNT4 $ (SUM(J,CHECK4(J)) NE 0)=1;
ABORT $(ERRORCNT4) "EXECUTION TERMINATED NO CSA WITHIN FARENF OF ASP";

*ASP MUST NOT BE PLACED TOO CLOSE TO THE FLOT.

PARAMETER CHECK4A(J) error check for asp flot straight line distance ;
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          CHECK4A(J) $ (ASPFLOT(J) LE 20)=1 ;
PARAMETER ERRORCNT4A error check four a ;
          ERRORCNT4A $ (SUM(J, CHECK4A(J)) NE 0)=1 ;
ABORT $(ERRORCNT4A) "EXECUTION TERMINATED ASP TO CLOSE TO FLOT" ;

*CSA MUST NOT BE PLACED TOO CLOSE TO THE FLOT.

PARAMETER CHECK4B(K) error check for csa flot straight line distance ;
          CHECK4B(K) $ (CSAFLOT(K) LE 50)=1 ;
PARAMETER ERRORCNT4B error check four b ;
          ERRORCNT4B $ (SUM(K, CHECK4B(K)) NE 0)=1 ;
ABORT $(ERRORCNT4B) "EXECUTION TERMINATED CSA TO CLOSE TO FLOT" ;

*AS DEFINED IN THE PROGRAM, PENALTY COSTS WILL VARY BETWEEN 1.00 AND
*4.00. THE FOLLOWING WILL INSURE CORRECT COMPUTATION.

PARAMETER CHECK5(I,J) error check for penalty cost calculations;
 CHECK5(I,J) $ (PNCOST1(I,J) GT 4.0 OR PNCOST1(I,J) LT 1.0)=1;
PARAMETER ERRORCNT5 error check five;
          ERRORCNT5 $ (SUM((I,J),CHECK5(I,J)) NE 0)=1;
ABORT $(ERRORCNT5) "EXECUTION TERMINATED PENALTY COST MISCALCULATION";

PARAMETER CHECK5A(J,K) error check for penalty cost calculations;
 CHECK5A(J,K) $ (PNCOST2(J,K) GT 4.0 OR PNCOST2(J,K) LT 1.0)=1;
PARAMETER ERRORCNT5A error check five a;
          ERRORCNT5A $ (SUM((J,K),CHECK5A(J,K)) NE 0)=1;
ABORT $(ERRORCNT5A) "EXECUTION TERMINATED PENALTY COST MISCALCULATION";

PARAMETER CHECK6(I,K) error check for penalty cost calculations;
 CHECK6(I,K) $ (PNCOST3(I,K) GT 4.0 OR PNCOST3(I,K) LT 1.0)=1;
PARAMETER ERRORCNT6 error check six;
          ERRORCNT6 $ (SUM((I,K),CHECK6(I,K)) NE 0)=1;
ABORT $(ERRORCNT6) "EXECUTION TERMINATED PENALTY COST MISCALCULATION" ;

*THIS ERROR CHECK WILL INSURE THAT THE DEMAND DATA IS IN QUANTITIES
*THAT THE ATP CAN REASONABLE HANDLE.

PARAMETER CHECK7(I,T) error check for demand at atp i ;
          CHECK7(I,T) $ (DMNATP(I,T) GT 2.300)=1 ;
PARAMETER ERRORCNT7 error check seven ;
          ERRORCNT7 $ (SUM((I,T), CHECK7(I,T)) NE 0)=1 ;
ABORT $(ERRORCNT7) "EXECUTION TERMINATED DEMAND EXCEED ATP CAPACITY" ;

VARIABLES X(I,J,K) csa k services asp j which services atp i
*                  (1=yes and 0=no)
          Z(I,K)   csa k services atp i (1=yes and 0=no)
          Y(J)     asp located at site j (1=yes and 0=no)
          B(K)     csa located at site k (1=yes and 0=no)
          COST     objective variable ;

BINARY VARIABLES X,Z,Y,B ;

EQUATIONS
 ONESITE(I)      assign atp to one asp and one csa
 SERVICE(J)      asp services two atps
 SUPPORT(K)      csa services two asps
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 SINGLE(I)          assign atp to one csa
 HELP(K)            csa services four atps
 VARUPBD1(I,J,K) variable upper bound for x ijk
 VARUPBD2(I,J,K) variable upper bound for x ijk
 VARUPBD3(I,K)    variable upper bound for z ik
 LIMIT              number of asps are limited by numasp
 CEILING            number of csas are limited by numcsa
 OBJFCN             definition of cost ;


 ONESITE(I)..       SUM((J,K) $ (MAXDIST(I,J) AND MAXLENG(J,K)),
                    X(I,J,K))=E=1 ;

 SERVICE(J)..       SUM((I,K) $ (MAXDIST(I,J) AND MAXLENG(J,K)),
                    X(I,J,K))=E=CORRES*Y(J) ;

 SUPPORT(K)..       SUM((I,J) $ (MAXDIST(I,J) AND MAXLENG(J,K)),
                    X(I,J,K))=E=RLTN*B(K) ;

 SINGLE(I)..        SUM(K $ MAXFAR(I,K), Z(I,K))=E=1 ;

 HELP(K)..          SUM(I $ MAXFAR(I,K), Z(I,K))=E=CONFIG*B(K) ;

 VARUPBD1(I,J,K) $ (MAXDIST(I,J) AND MAXLENG(J,K)).. X(I,J,K)=L=Y(J) ;

 VARUPBD2(I,J,K) $ (MAXDIST(I,J) AND MAXLENG(J,K)).. X(I,J,K)=L=B(K) ;

 VARUPBD3(I,K) $ MAXFAR(I,K).. Z(I,K)=L=B(K) ;

 LIMIT..            SUM(J,Y(J))=E=NUMASP ;

 CEILING..          SUM(K,B(K))=E=NUMCSA ;

 OBJFCN..           COST=E=
  SUM((I,J,K,T) $ (MAXDIST(I,J) AND MAXLENG(J,K)), ((PORASP*
  PNCOST1(I,J)*DIST(I,J)*TUNE*DMNATP(I,T))+(PORCSA*PNCOST2(J,K)*
  LENGTH(J,K)*TUNE*DMNATP(I,T)))*X(I,J,K)) + SUM((I,K,T) $ MAXFAR(I,K),
  PERCSA*PNCOST3(I,K)*HOWFAR(I,K)*TUNE*DMNATP(I,T)*Z(I,K)) +
  SUM(J, PROX(J)*Y(J)) + SUM(K, CLOSE(K)*B(K)) ;

MODEL LOCATION /ONESITE, SERVICE, SUPPORT, SINGLE, HELP, VARUPBD1,
                VARUPBD2, VARUPBD3, LIMIT, CEILING, OBJFCN/ ;

OPTION LIMROW=12, LIMCOL=0, ITERLIM=5000, OPTCR=0.01;
*OPTION RESLIM=0.00 ;

SOLVE LOCATION USING MIP MINIMIZING COST ;

DISPLAY X.L, Z.L, Y.L, B.L ;

*THE FOLLOWING FOUR ERROR CHECKS INSURE BINARY DATA IS PASSED FROM THE
*FACILITY LOCATION SUBMODEL TO THE NETWORK FLOW SUBMODEL. IF ANY DATA
*IS NOT BINARY, THE PROGRAM WILL ABORT.

PARAMETER CHECK8(I,J,K) error check for x ijk support path ;
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          CHECK8(I,J,K) $ (X.L(I,J,K) NE 1 AND X.L(I,J,K) NE 0)=1 ;
PARAMETER ERRORCNT8 error check eight ;
          ERRORCNT8 $ (SUM((I,J,K), CHECK8(I,J,K)) NE 0)=1 ;
ABORT $(ERRORCNT8) "EXECUTION TERMINATED X IS NOT BINARY" ;

PARAMETER CHECK9(I,K) error check for z ik throughput path ;
          CHECK9(I,K) $ (Z.L(I,K) NE 1 AND Z.L(I,K) NE 0)=1 ;
PARAMETER ERRORCNT9 error check nine ;
          ERRORCNT9 $ (SUM((I,K), CHECK9(I,K)) NE 0)=1 ;
ABORT $(ERRORCNT9) "EXECUTION TERMINATED Z IS NOT BINARY" ;

PARAMETER CHECK10(J) error check for y j facility opening ;
          CHECK10(J) $ (Y.L(J) NE 1 AND Y.L(J) NE 0)=1 ;
PARAMETER ERRORCNT10 error check ten ;
          ERRORCNT10 $ (SUM(J, CHECK10(J)) NE 0)=1 ;
ABORT $(ERRORCNT10) "EXECUTION TERMINATED Y IS NOT BINARY" ;

PARAMETER CHECK11(K) error check for b k facility opening ;
          CHECK11(K) $ (B.L(K) NE 1 AND B.L(K) NE 0)=1 ;
PARAMETER ERRORCNT11 error check eleven ;
          ERRORCNT11 $ (SUM(K, CHECK11(K)) NE 0)=1 ;
ABORT $(ERRORCNT11) "EXECUTION TERMINATED B IS NOT BINARY" ;

*THE FOLLOWING FIVE PARAMETERS ARE USER ADJUSTABLE TACTICAL COSTS
*FOR MOVING AND HOLDING AMMUNITION.................

PARAMETER SHIP1(J,K,T) shipping cost from csa k to asp j in period t ;
          SHIP1(J,K,T)=1.00 ;

PARAMETER SHIP2(I,J,T) shipping cost from asp j to atp i in period t ;
          SHIP2(I,J,T)=1.00  ;

PARAMETER SHIP3(I,K,T) shipping cost from csa k to atp i in period t ;
          SHIP3(I,K,T)=1.00 ;

PARAMETER INV1(J,T) inventory cost at asp j in period t ;
          INV1(J,T)=1.00 ;

*THE FOLLOWING FIVE SETS WILL BE USED TO SET UP "SUCH THAT"
*OPERATORS BASED ON THE OPTIMAL SOLUTION OF THE LOCATION
*PROBLEM TO REDUCE THE NUMBER OF CONSTRAINTS IN THE
*NETWORK FLOW MODEL TO THE MINIMUM POSSIBLE.........

SETS ASSG(J,K) each asp j supported by one csa k ;
     ASSG(J,K)=YES $ (SUM(I,X.L(I,J,K))) ;

SETS SPPT(I,J) each atp i supported by one asp j ;
     SPPT(I,J)=YES $ (SUM(K,X.L(I,J,K))) ;

SETS DIRC(I,K) each atp i supported by one csa k ;
     DIRC(I,K)=YES $ Z.L(I,K) ;

SETS ASPOPEN(J) filter for network flow and lift capacities ;
     ASPOPEN(J)=YES $ Y.L(J) ;

SETS CSAOPEN(K) filter for network flow and lift capacities ;
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     CSAOPEN(K)=YES $ B.L(K) ;

*THIS SET ESTABLISHES A TIME PERIOD IN WHICH INVENTORY IS REQUIRED
*TO BE A BOUNDED VARIABLE.....

SETS TWNINE(T) time period one through twenty-nine ;
     TWNINE(T)=YES $ (ORD(T) LT CARD(T)) ;

DISPLAY ASSG, SPPT, DIRC, ASPOPEN, CSAOPEN, TWNINE ;

SCALARS MAXCSA  maximum lift capacity of the csa /10.664/
        MAXASP  maximum lift capacity of the asp /2.732/
        TRIPS   possible round trips per day from csa k to atp i /3/
        ROUND   possible round trips per day from csa k to asp j /4/
        TIMES   possible round trips per day from asp j to atp i /12/
        TRUCKS  number of tractor trailers authorized per Corps /300/
        AVGHAUL average haul weight per trailer /.015/
        AVAIL   tractor availability on any given day /.80/
        AMMO    percentage of total tractor trailers hauling ammo /.80/
        LEVEL   work level devote to issue at csa over time /.333/
        MAXINV  maximum inventory of the asp in days of supply /5/
        MININV  minimum inventory of the asp in days of supply /1/ ;

VARIABLES F(J,K,T)  flow from csa k to asp j in period t
          TH(I,K,T) flow from csa k to atp i in period t
          EF(I,J,T) flow from asp j to atp i in period t
          IASP(J,T) inventory at asp j at the end of time period t
          NCOST     new objective variable ;

POSITIVE VARIABLES F, TH, EF, IASP ;

*ESTABLISH INVENTORY UPPER AND LOWER BOUNDS AS APPROPRIATE.......
IASP.UP(J,T) $ TWNINE(T) =SUM(I $ SPPT(I,J),
             DMNATP(I,T+1))*MAXINV $ ASPOPEN(J) ;
IASP.LO(J,T) $ TWNINE(T) =SUM(I $ SPPT(I,J),
             DMNATP(I,T+1))*MININV $ ASPOPEN(J) ;

EQUATIONS
 BALASP(J,T)     flow into asp j must equal flow out
 BALATP(I,T)     flow into atp i must equal flow out
 CAPCSA(K,T)     lift capacity of csa
 CAPASP(J,T)     lift capacity of asp
 STABLE(K)       surrogate long run flow balance for csa k
 TRANS(T)        trans assets available to haul ammo in time period t
 LONGRUN         bypass long run contribution to demand
 NOBJFCN         new definition of cost ;


 BALASP(J,T) $ ASPOPEN(J).. -SUM(K $ ASSG(J,K), F(J,K,T))+SUM(I $
                  SPPT(I,J), EF(I,J,T))-IASP(J,T-1)+IASP(J,T)=E=0 ;

 BALATP(I,T)..     -SUM(J $ SPPT(I,J), EF(I,J,T))-SUM(K $ DIRC(I,K),
                  TH(I,K,T))=E=-DMNATP(I,T) ;

 CAPCSA(K,T) $ CSAOPEN(K).. SUM(J $ ASSG(J,K), F(J,K,T))+
                  SUM(I $ DIRC(I,K), TH(I,K,T))=L=MAXCSA ;
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CAPASP(J,T) $ ASPOPEN(J).. SUM(K $ ASSG(J,K), F(J,K,T))+
                       SUM(I $ SPPT(I,J), EF(I,J,T))=L=MAXASP ;

STABLE(K)   $ CSAOPEN(K).. SUM((I,T) $ DIRC(I,K), TH(I,K,T))+
                       SUM((J,T) $ ASSG(J,K), F(J,K,T))=L=LEVEL*
                       CARD(T)*MAXCSA ;

TRANS(T)..             (SUM((I,K) $ DIRC(I,K), TH(I,K,T))/TRIPS)+
                       (SUM((J,K) $ ASSG(J,K), F(J,K,T))/ROUND)=L=
                       TRUCKS*AVGHAUL*AVAIL*AMMO ;

LONGRUN..              SUM((I,K,T) $ DIRC(I,K), TH(I,K,T))=G=
                       PERCSA*SUM((I,T), DMNATP(I,T)) ;

NOBJFCN..              NCOST=E=
                       SUM((J,K,T) $ ASSG(J,K),
                                   SHIP1(J,K,T)*F(J,K,T))+
                       SUM((I,J,T) $ SPPT(I,J),
                                   SHIP2(I,J,T)*EF(I,J,T))+
                       SUM((I,K,T) $ DIRC(I,K),
                                   SHIP3(I,K,T)*TH(I,K,T))+
                       SUM((J,T) $ ASPOPEN(J), INV1(J,T)*IASP(J,T)) ;


MODEL STOCKAGE /BALASP, BALATP, CAPCSA, CAPASP,
                STABLE, TRANS, LONGRUN, NOBJFCN/ ;

OPTION LIMROW=4, LIMCOL=0 ;
*OPTION RESLIM=0.00 ;

SOLVE STOCKAGE USING LP MINIMIZING NCOST ;

OPTION EJECT ;

DISPLAY F.L, IASP.L, TH.L, EF.L ;

OPTION EJECT ;

*THE FOLLOWING ARE POST-OPTIMALITY CALCULATIONS TO DETERMINE THE NUMBER
*OF TRACTOR TRAILERS REQUIRED TO SUPPORT THE NETWORK..................

PARAMETER TRANSF(J,K,T) tractor trailers needed on jk arc ;
          TRANSF(J,K,T)=F.L(J,K,T)/AVGHAUL ;

PARAMETER TRANSEF(I,J,T) tractor trailers needed on ij arc ;
          TRANSEF(I,J,T)=EF.L(I,J,T)/AVGHAUL ;

PARAMETER TRANSTH(I,K,T) tractor trailers needed on ik arc ;
          TRANSTH(I,K,T)=TH.L(I,K,T)/AVGHAUL ;

PARAMETER STRANSF(T) total tractor trailers needed in time period t ;
          STRANSF(T)=SUM((J,K), TRANSF(J,K,T)) ;

PARAMETER STRANSEF(T) total tractor trailers needed in time period t ;
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          STRANSEF(T)=SUM((I,J), TRANSEF(I,J,T)) ;

PARAMETER STRANSTH(T) total tractor trailers needed in time period t ;
          STRANSTH(T)=SUM((I,K), TRANSTH(I,K,T)) ;

PARAMETER TIMETOT(T) total corps requirement for time period t ;
          TIMETOT(T)=STRANSF(T)+STRANSEF(T)+STRANSTH(T) ;

DISPLAY TRANSF, STRANSF, TRANSEF, STRANSEF, TRANSTH,
        STRANSTH, TIMETOT ;
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8